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Hammond

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(54) **SYSTEM FOR BYPASSING A POWER CELL OF A POWER SUPPLY**

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(73) Assignee: **Siemens Industry, Inc.**, Alpharetta, GA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 387 days.

(21) Appl. No.: **11/857,646**

(22) Filed: **Sep. 19, 2007**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
H01H 9/54 (2006.01)

(52) **U.S. Cl.** **307/140**; 307/412

(58) **Field of Classification Search** 307/412, 307/140
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,625,545	A	4/1997	Hammond	
5,986,909	A	11/1999	Hammond et al.	
6,222,284	B1	4/2001	Hammond et al.	
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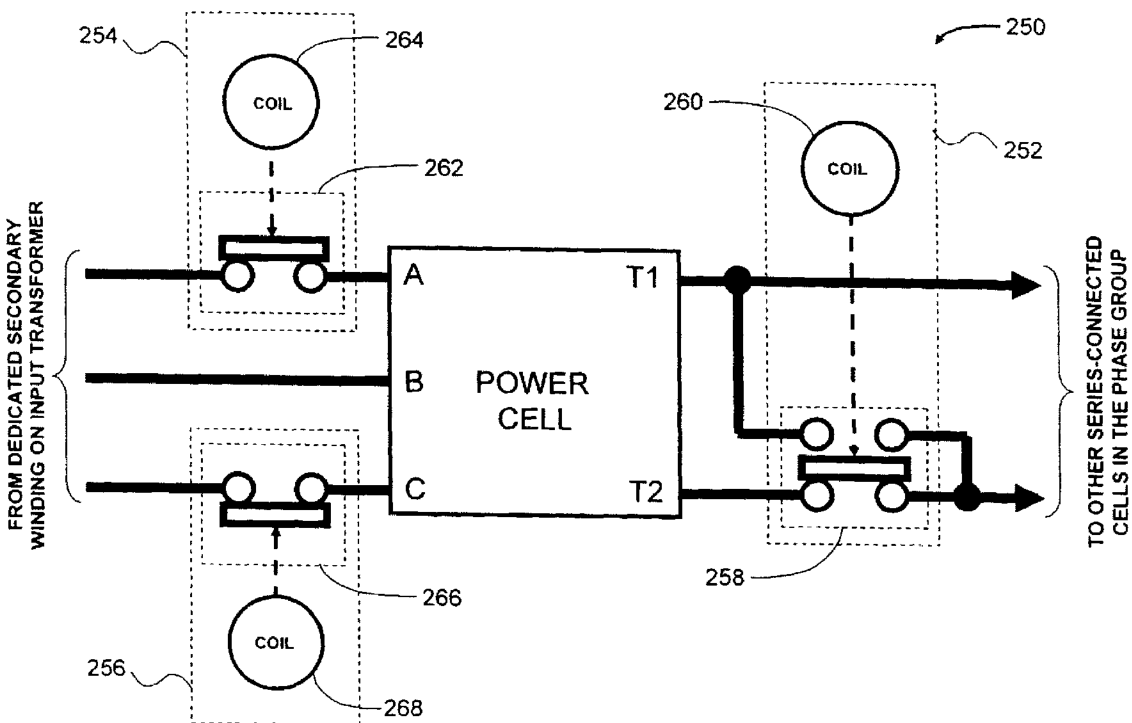
Primary Examiner—Robert L. DeBeradinis
(74) *Attorney, Agent, or Firm*—Filip A. Kowalewski

(57) **ABSTRACT**

A system. The system includes a multi-winding device having a primary winding and a plurality of three-phase secondary windings, and a plurality of power cells. Each power cell is connected to a different three-phase secondary winding of the multi-winding device. The system also includes a first contact connected to a first input terminal of at least one of the power cells, a second contact connected to a second input terminal of the at least one of the power cells, and a third contact connected to first and second output terminals of the at least one of the power cells.

20 Claims, 19 Drawing Sheets



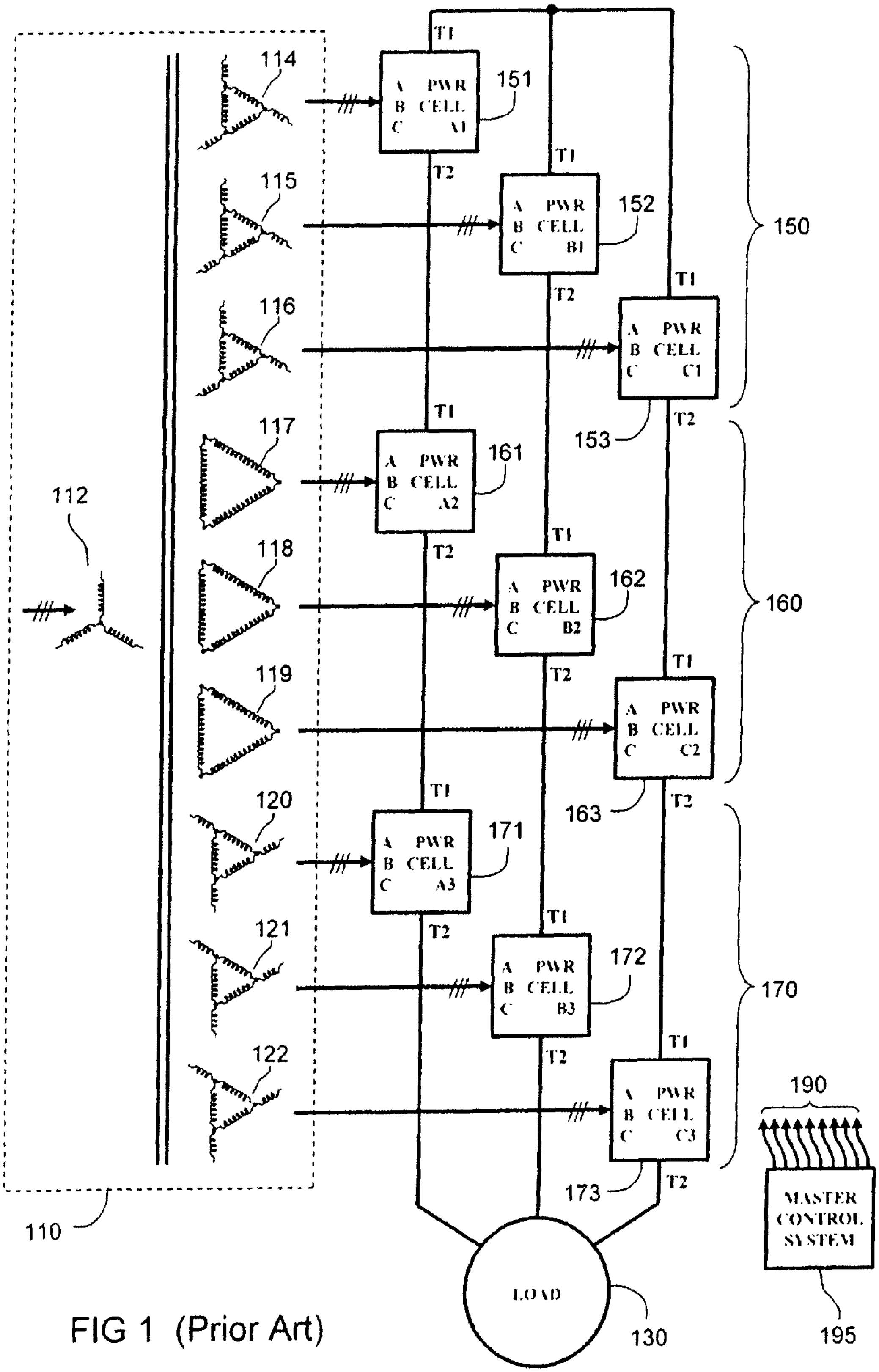


FIG 1 (Prior Art)

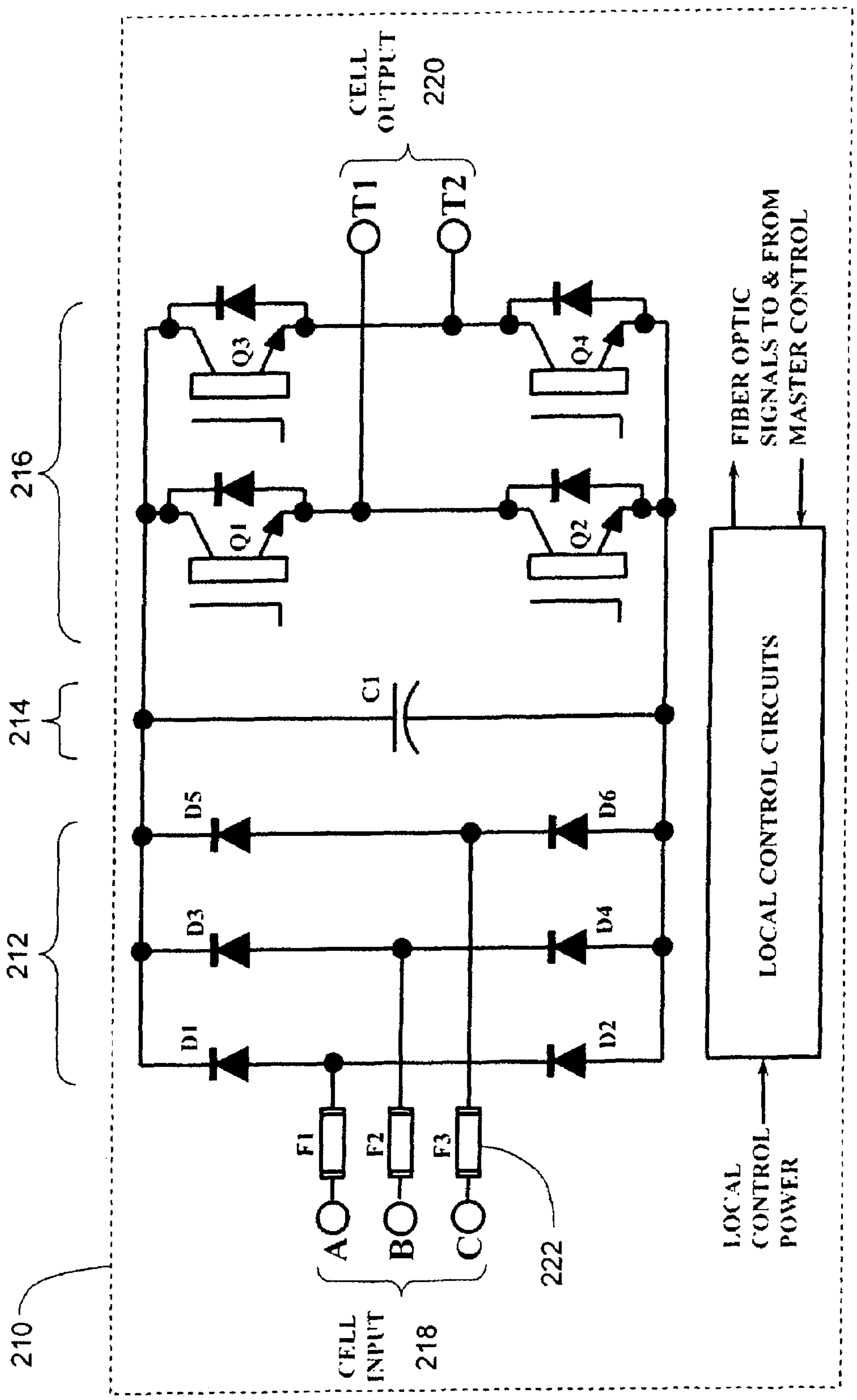


FIG 2 (Prior Art)

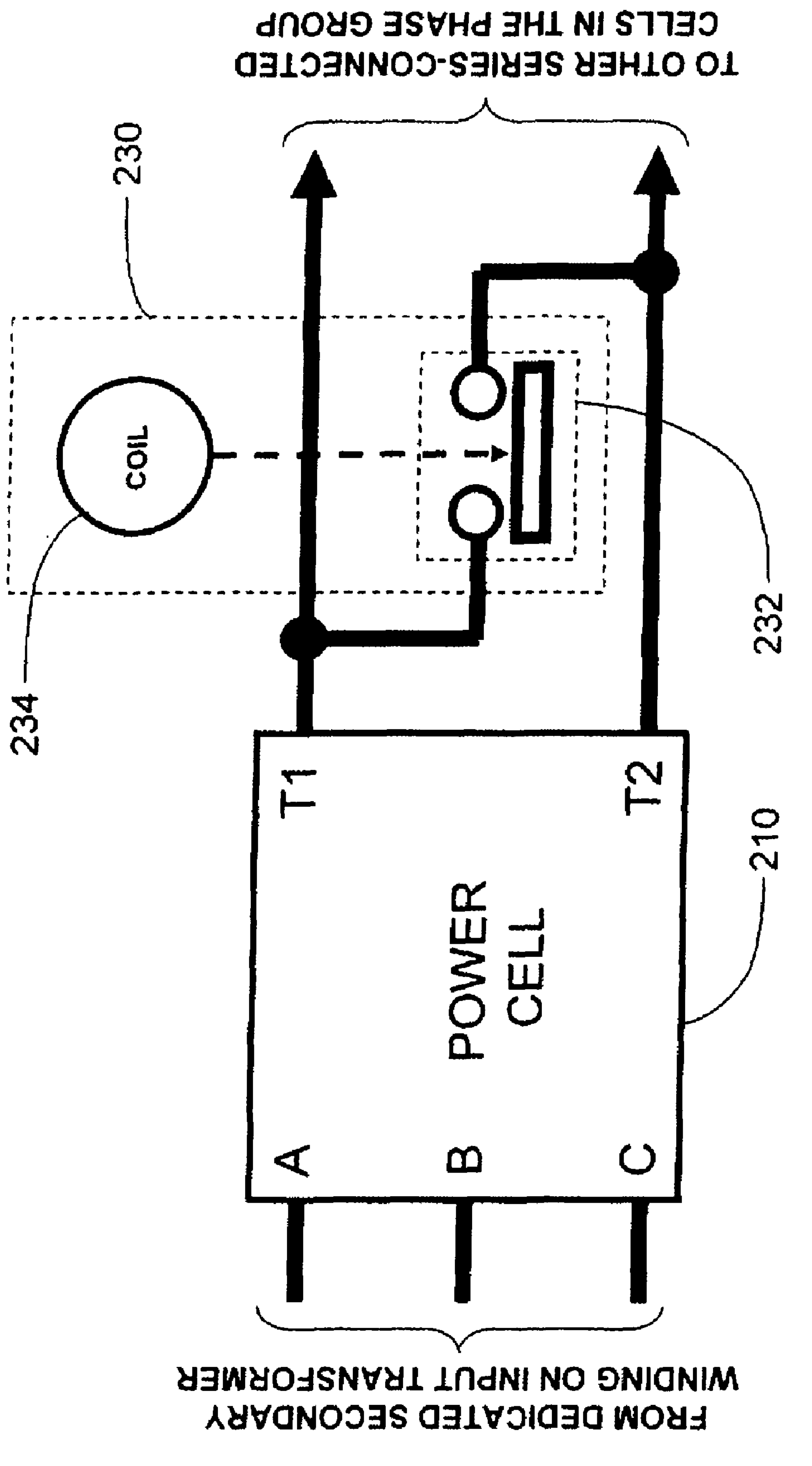


FIG 3 (Prior Art)

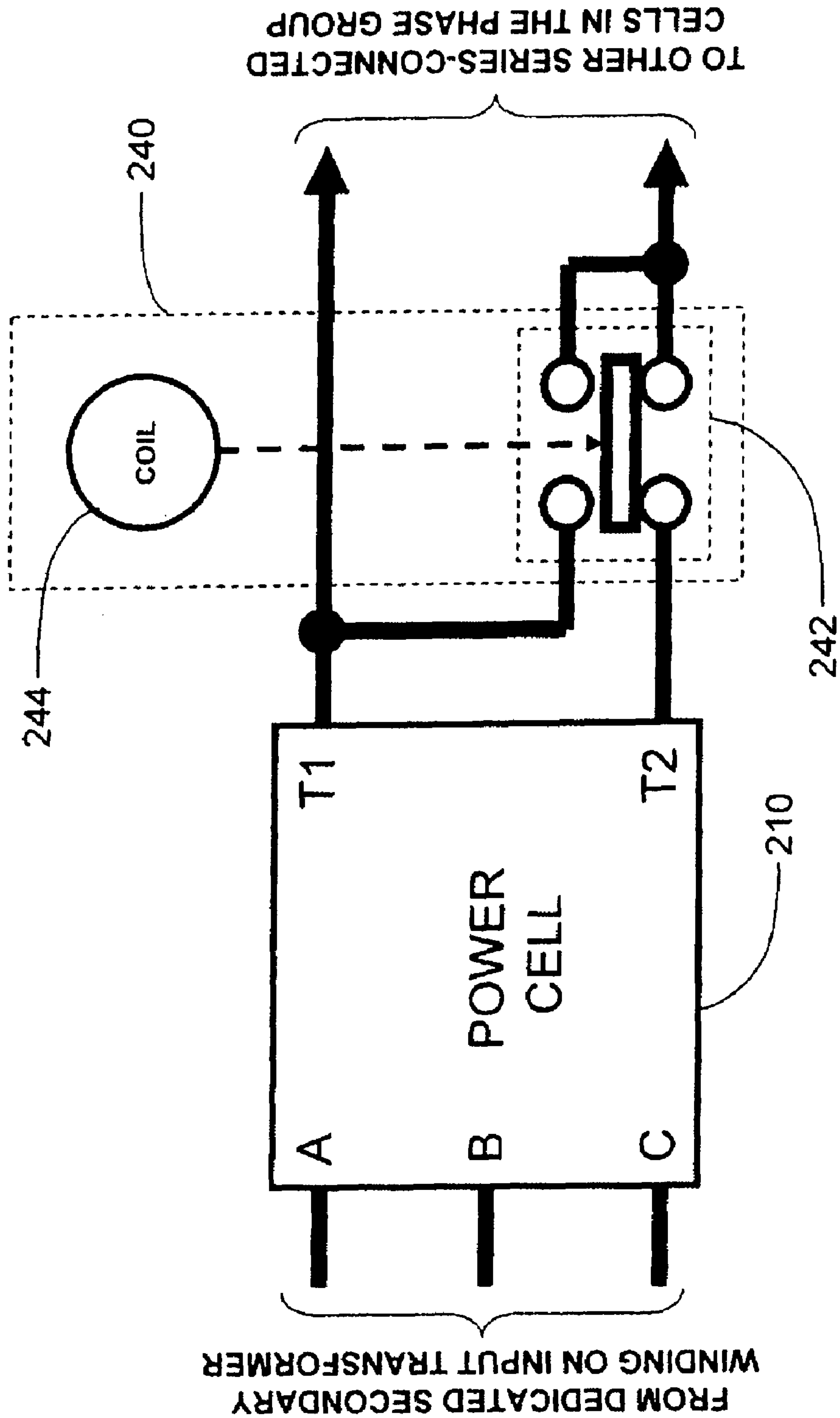


FIG 4 (Prior Art)

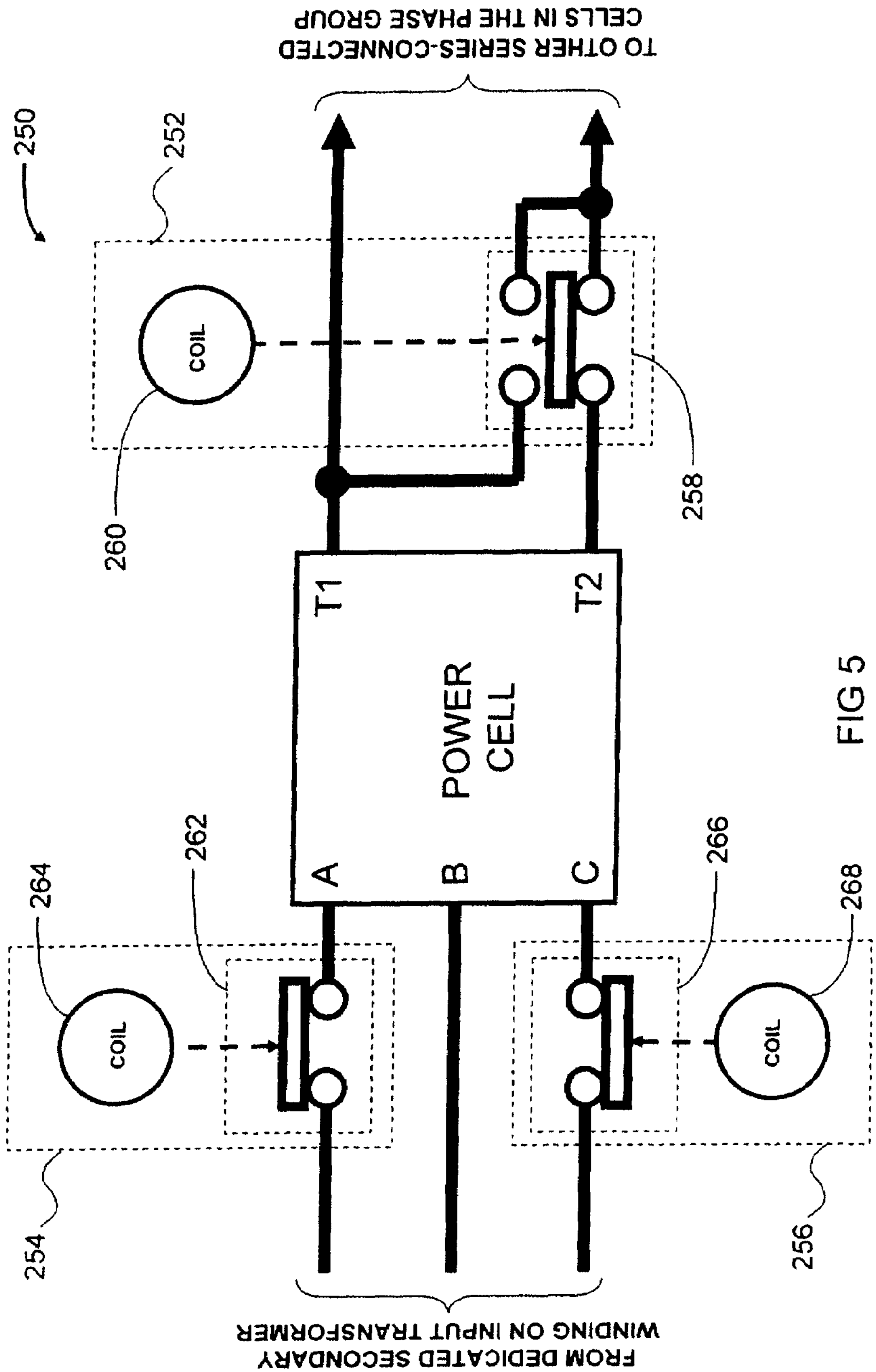
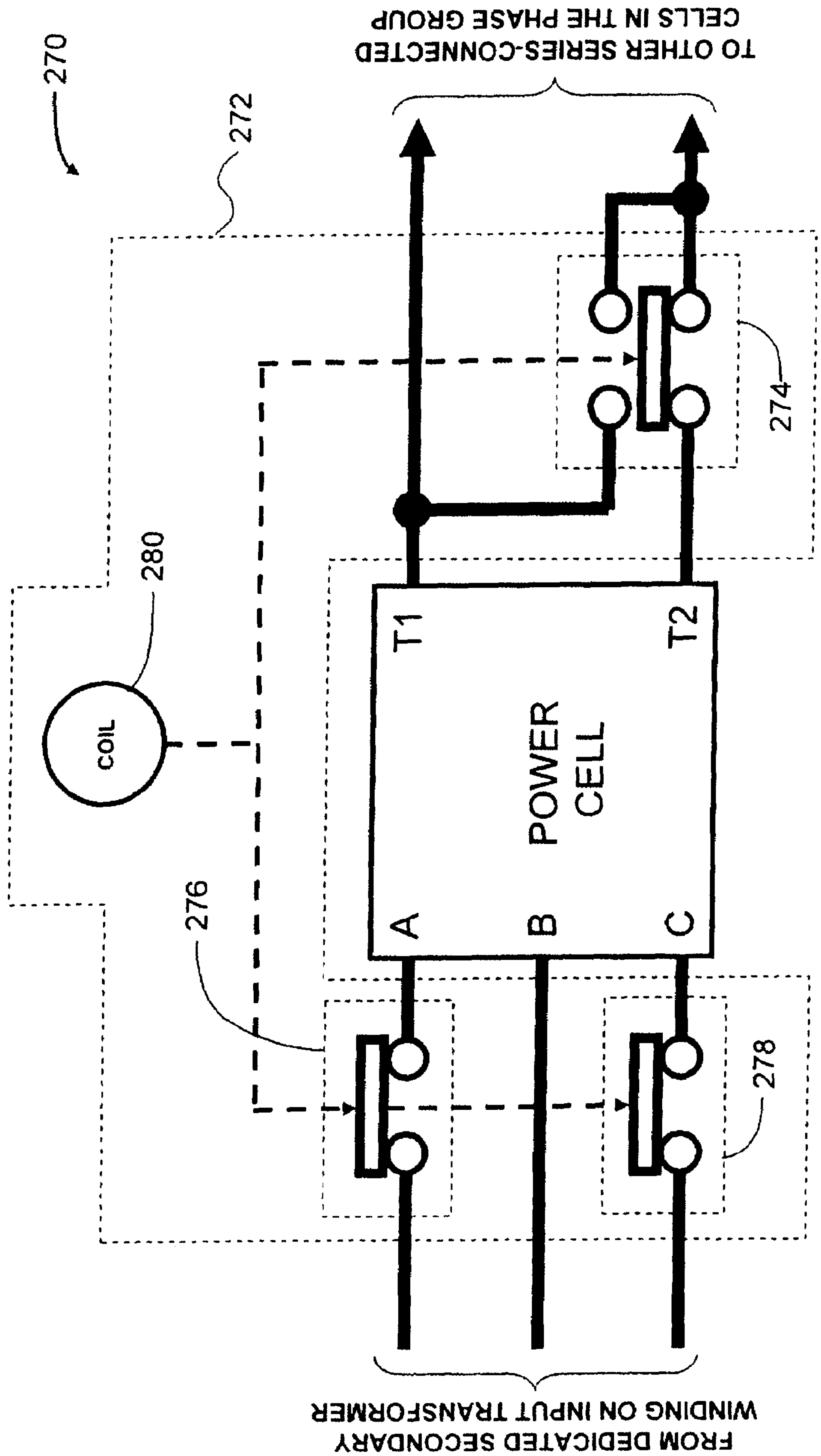

TO OTHER SERIES-CONNECTED
CELLS IN THE PHASE GROUP
250
252
COIL
260
258
T1
T2
POWER
CELL
A
B
C
262
264
266
268
COIL
COIL
254
256
FROM DEDICATED SECONDARY
WINDING ON INPUT TRANSFORMER

FIG 5



270
272
TO OTHER SERIES-CONNECTED CELLS IN THE PHASE GROUP
274
280
COIL
POWER CELL
T1
T2
A
B
C
276
278
FROM DEDICATED SECONDARY WINDING ON INPUT TRANSFORMER

FIG 6

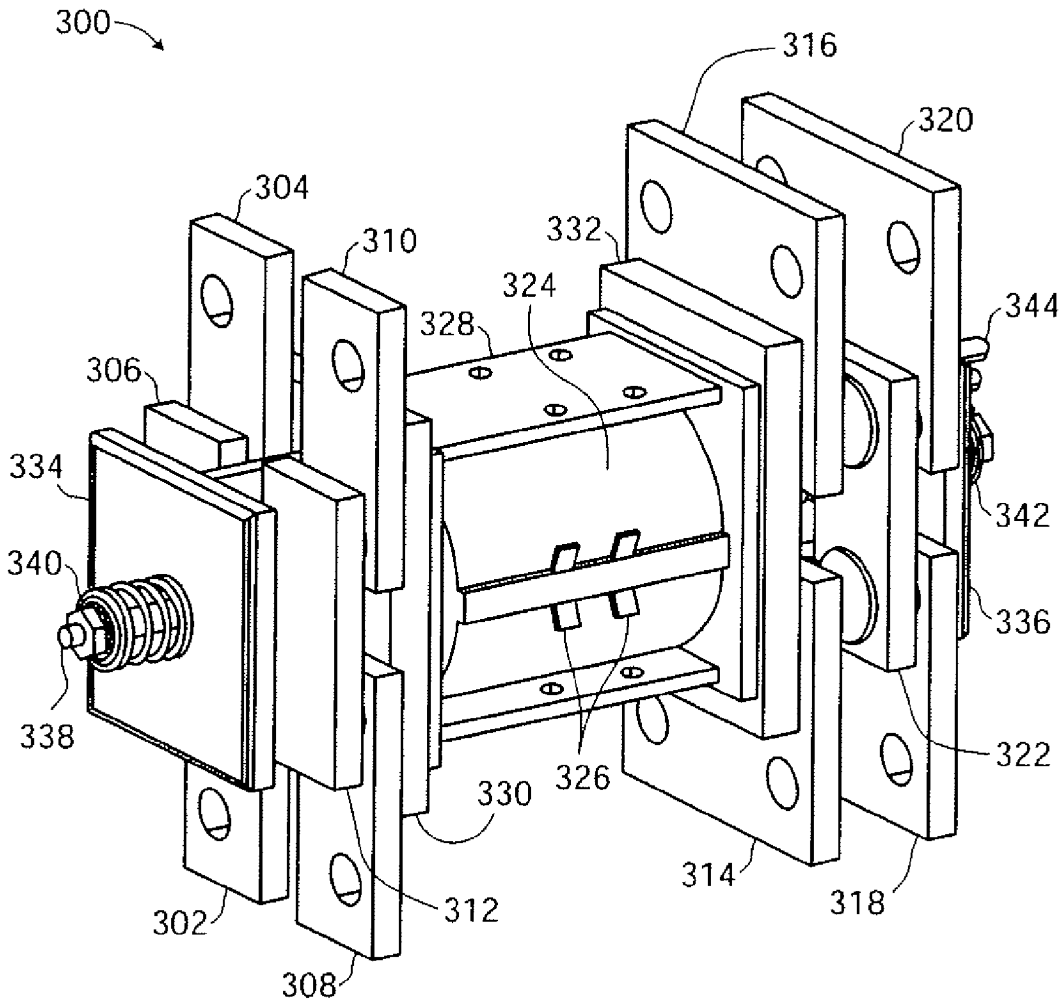

300
316
320
304
310
332
324
344
328
306
334
342
340
336
338
322
326
330
314
318
312
302
308

FIG. 7

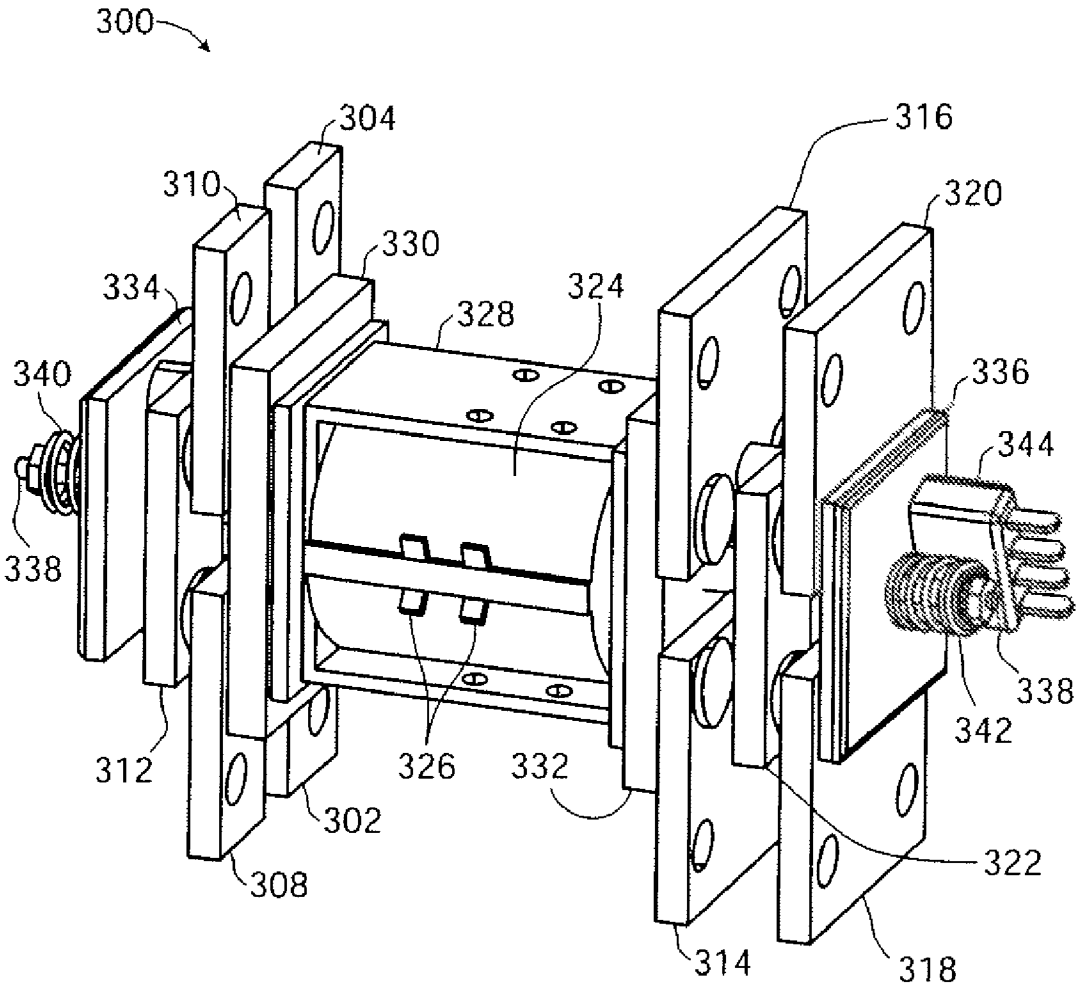

300
304
310
330
334
328
324
316
320
340
336
344
338
342
338
312
326
332
322
302
308
314
318

FIG. 8

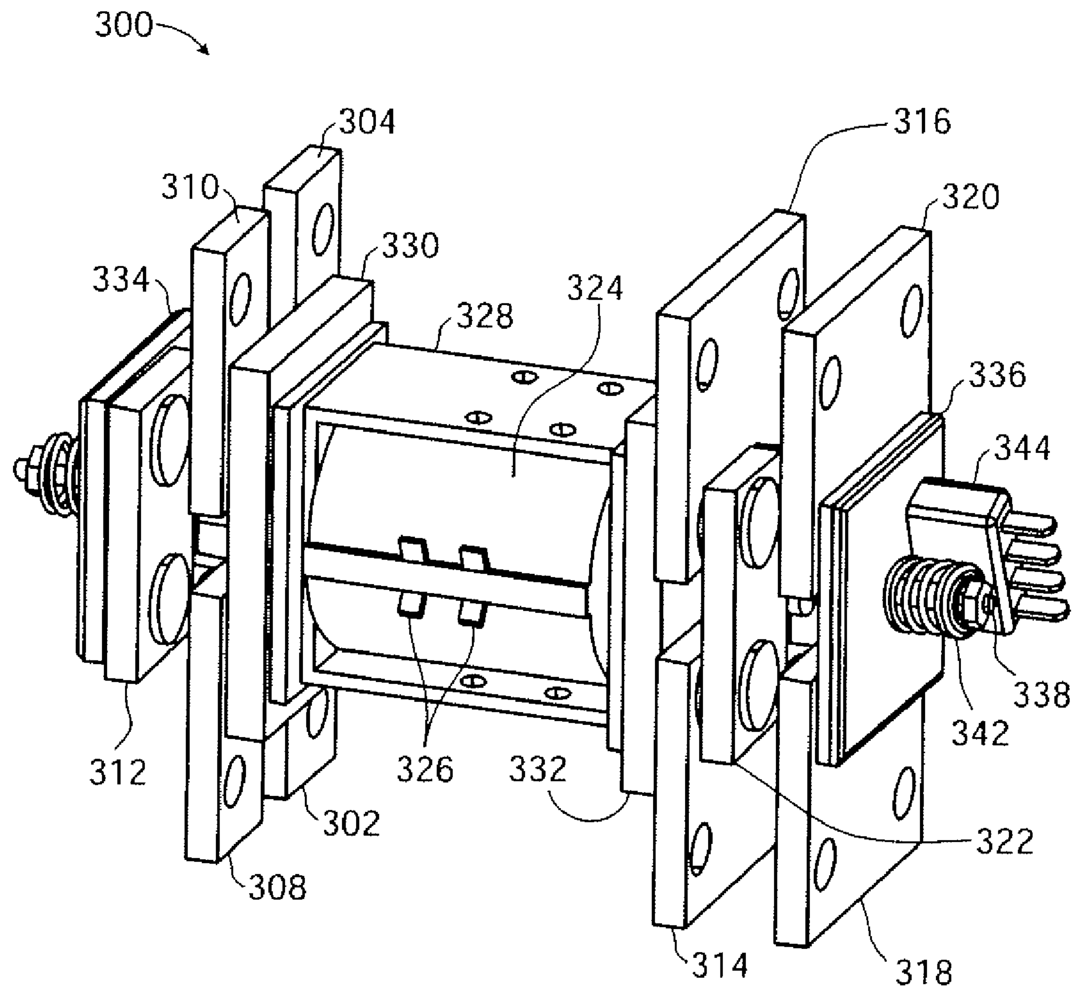

300
304
316
310
320
330
334
324
328
336
344
338
342
312
326
332
302
322
308
314
318

FIG. 9

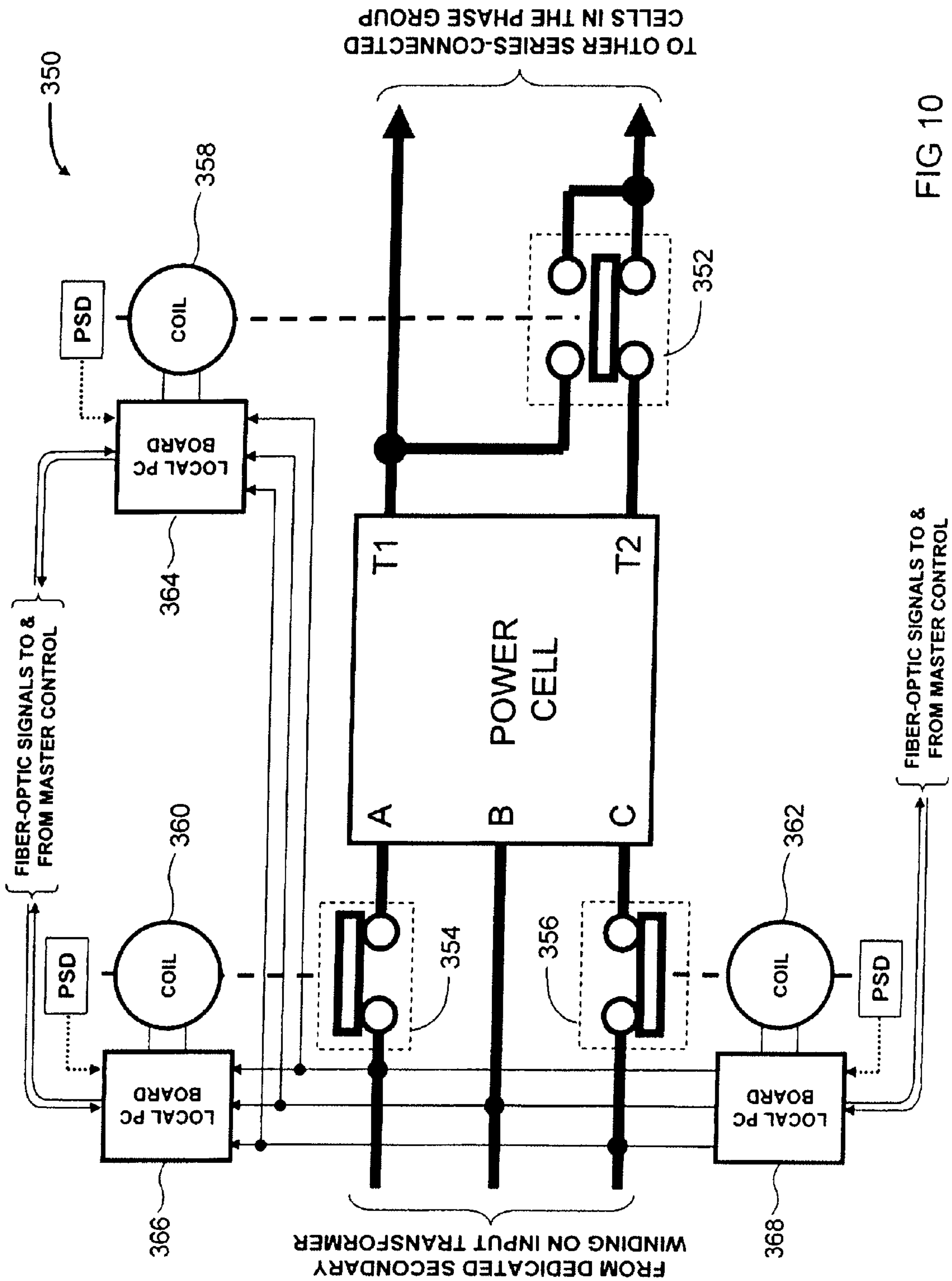

350
TO OTHER SERIES-CONNECTED
CELLS IN THE PHASE GROUP
PSD
COIL
358
352
LOCAL PC
BOARD
364
FIBER-OPTIC SIGNALS TO &
FROM MASTER CONTROL
T1
T2
POWER
CELL
A
B
C
360
362
354
356
366
368
FROM DEDICATED SECONDARY
WINDING ON INPUT TRANSFORMER

FIG 10

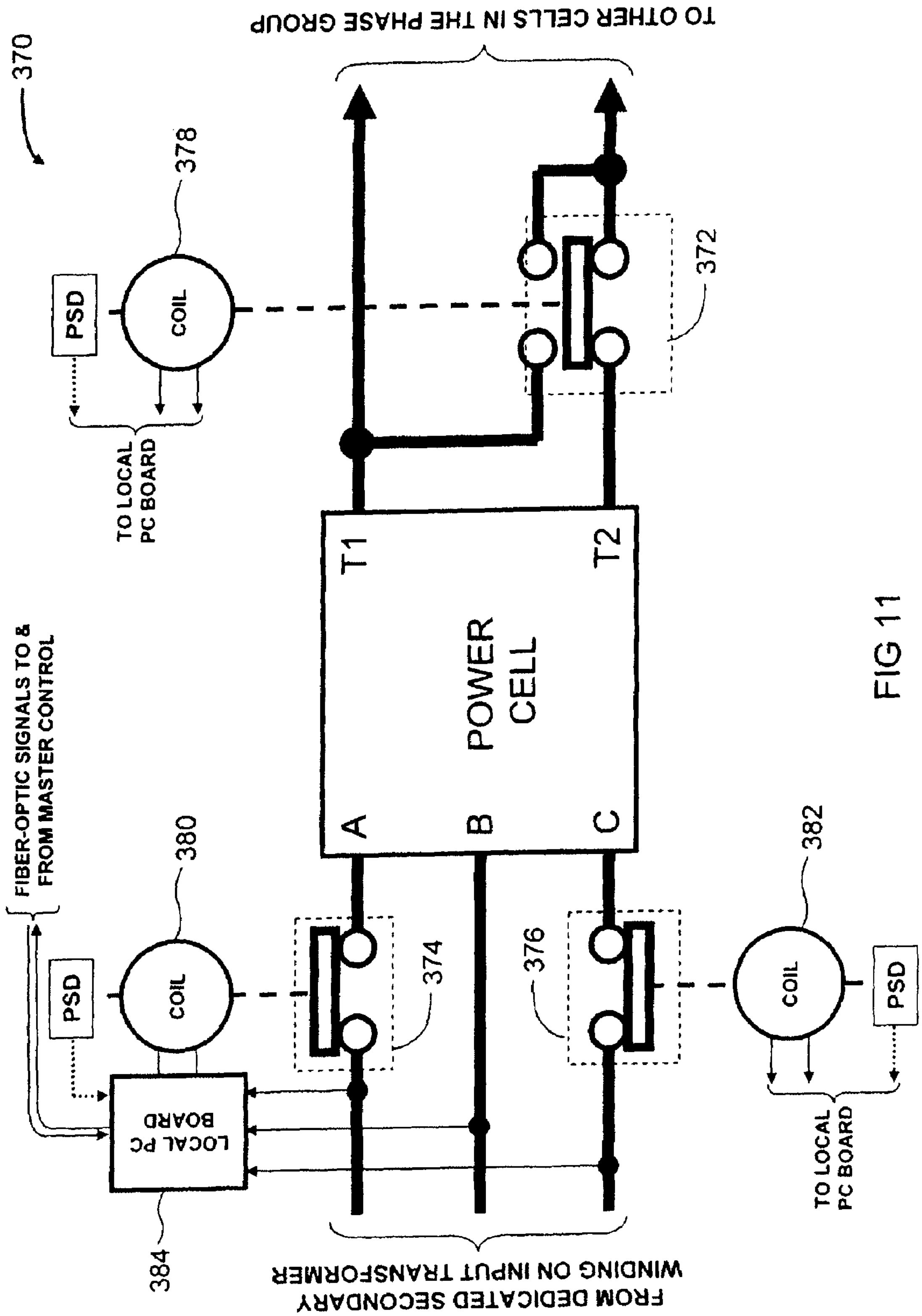

370
378
372
380
374
376
382
384
TO OTHER CELLS IN THE PHASE GROUP
PSD
COIL
TO LOCAL PC BOARD
FIBER-OPTIC SIGNALS TO & FROM MASTER CONTROL
POWER CELL
T1
T2
A
B
C
LOCAL PC BOARD
FROM DEDICATED SECONDARY WINDING ON INPUT TRANSFORMER

FIG 11

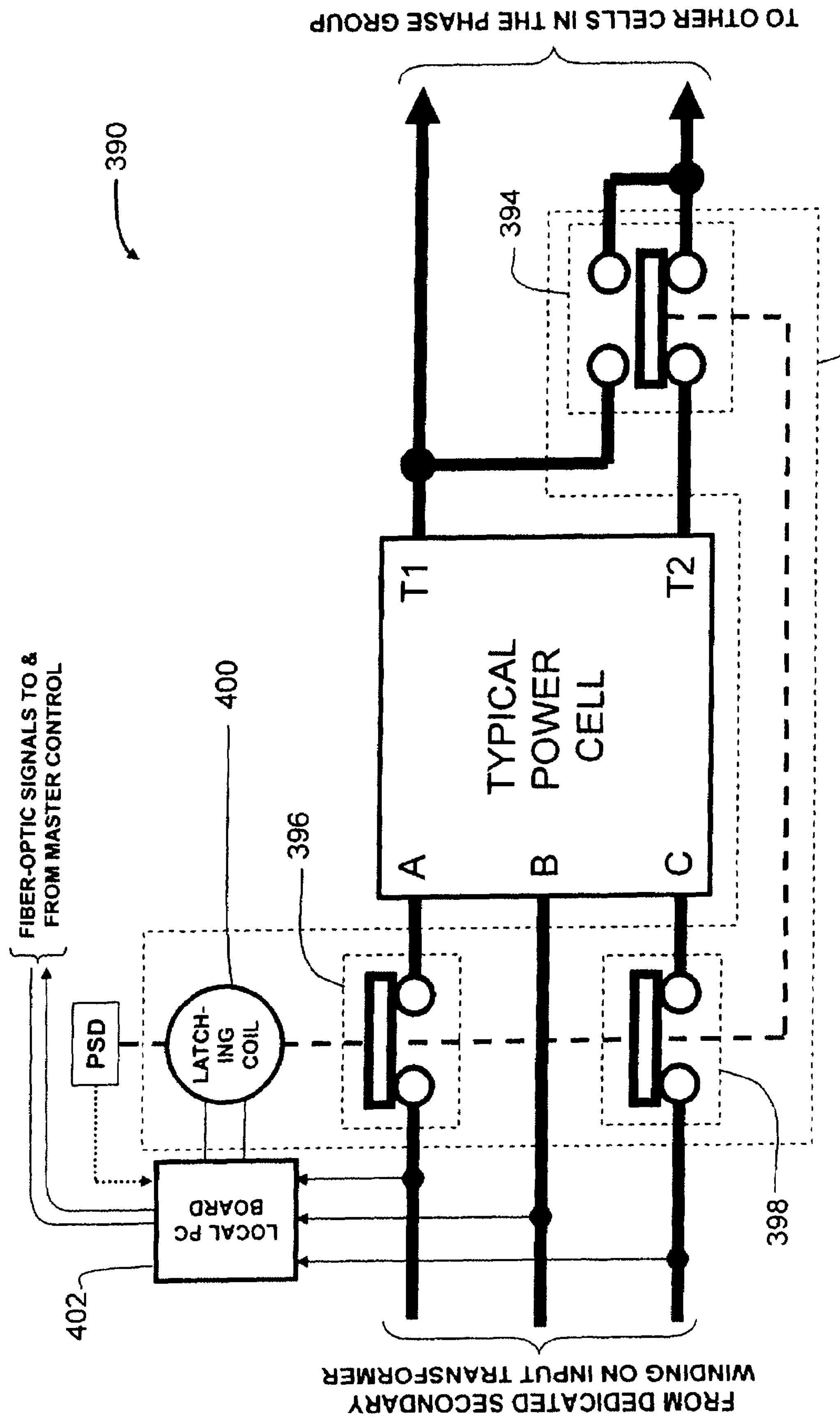

390
TO OTHER CELLS IN THE PHASE GROUP
394
392
TYPICAL POWER CELL
T1
T2
A
B
C
396
400
398
402
FIBER-OPTIC SIGNALS TO & FROM MASTER CONTROL
PSD
LATCH-ING COIL
LOCAL PC BOARD
FROM DEDICATED SECONDARY WINDING ON INPUT TRANSFORMER

FIG 12

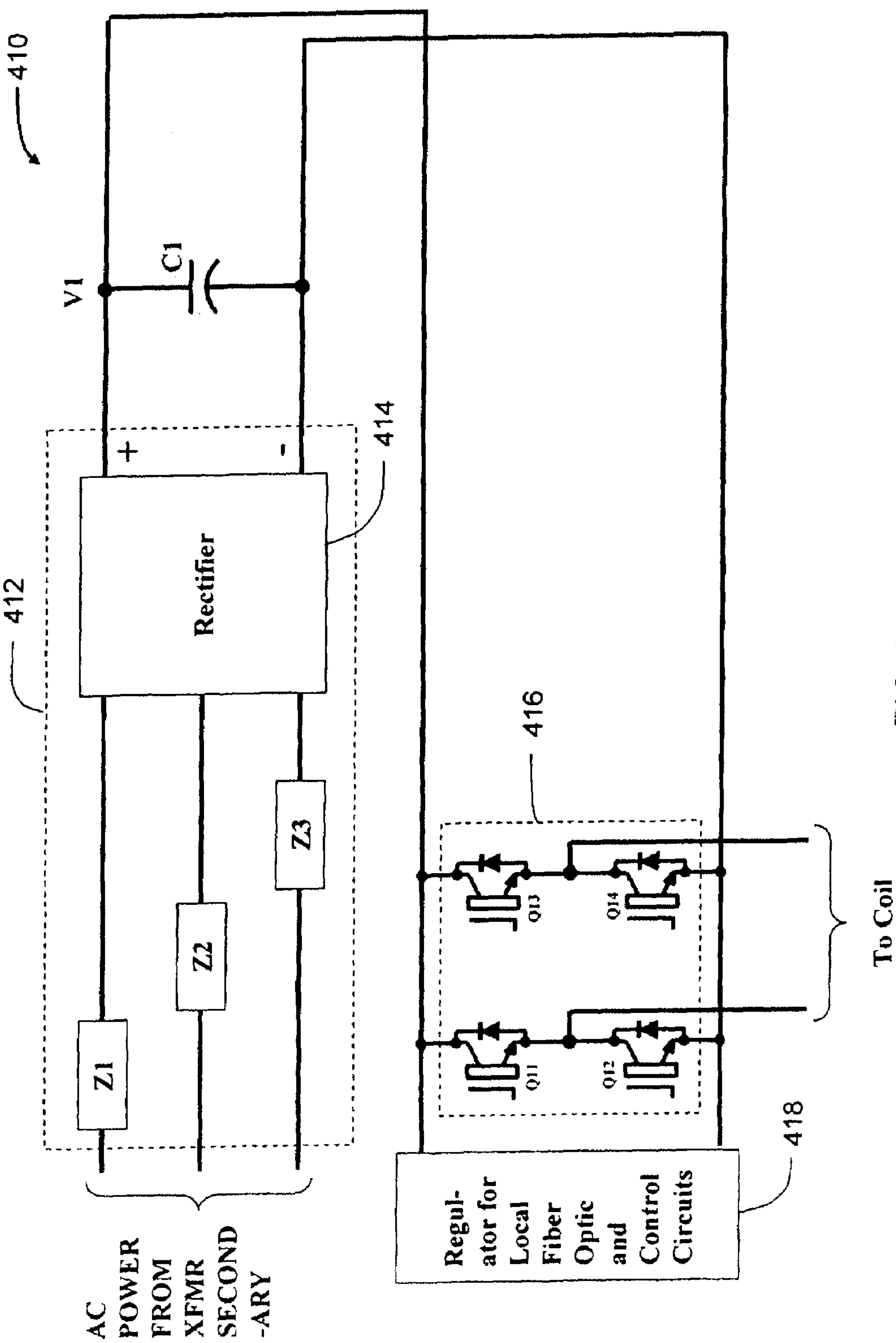

410
V1
C1
412
414
+
-
Rectifier
Z1
Z2
Z3
416
Q11
Q12
Q13
Q14
To Coil
418
AC POWER FROM XFMR SECOND -ARY
Regul- ator for Local Fiber Optic and Control Circuits

FIG 13

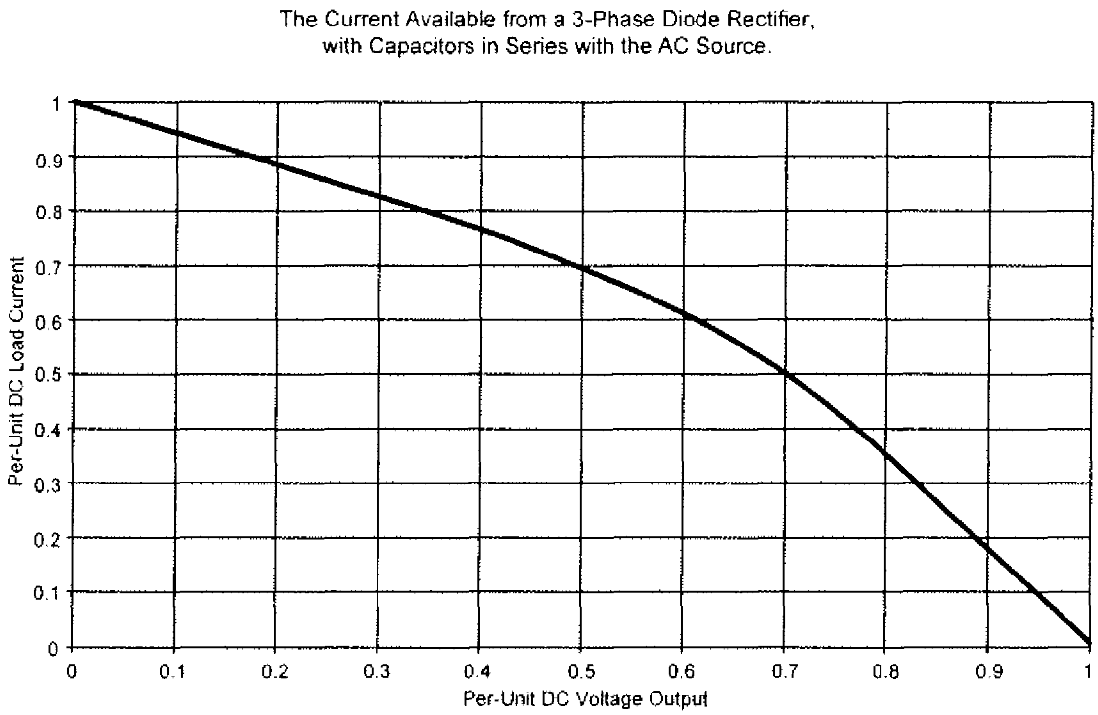

The Current Available from a 3-Phase Diode Rectifier,
with Capacitors in Series with the AC Source.
Per-Unit DC Load Current
Per-Unit DC Voltage Output
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

FIG. 14

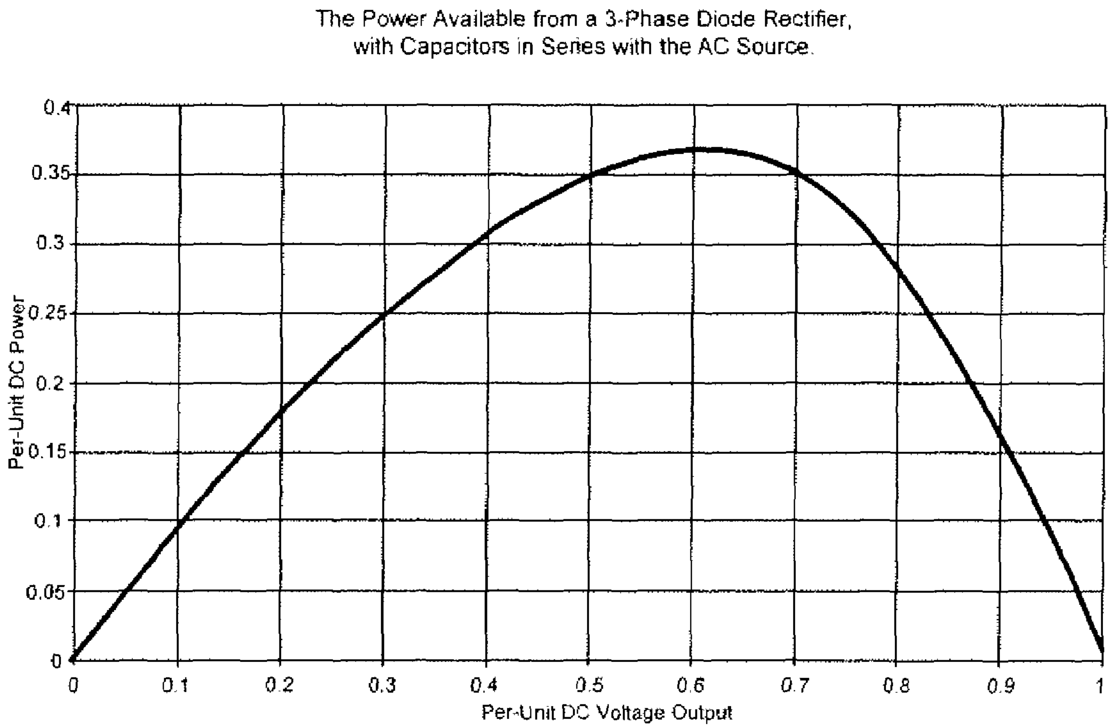
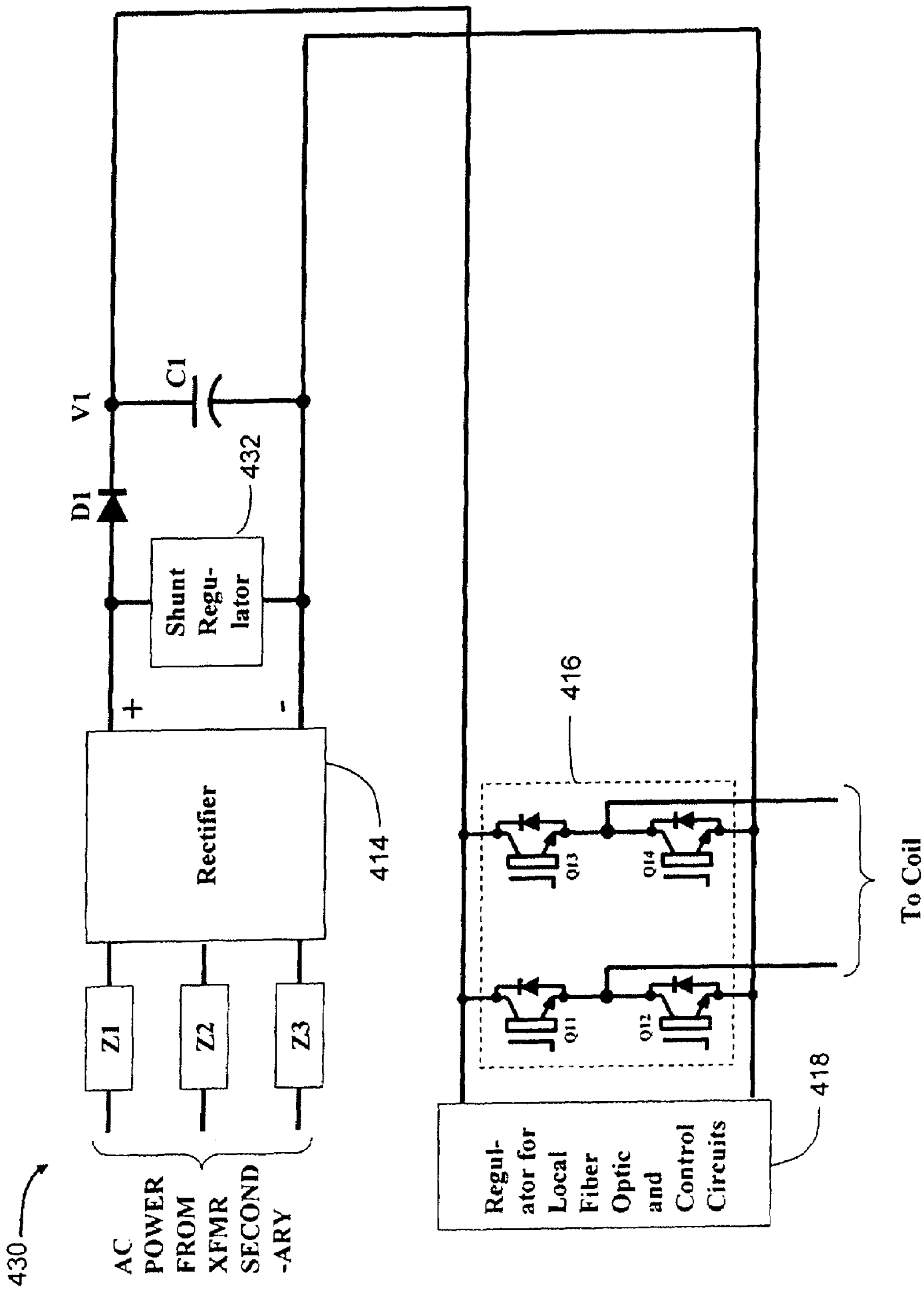

The Power Available from a 3-Phase Diode Rectifier,
with Capacitors in Series with the AC Source.
Per-Unit DC Power
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Per-Unit DC Voltage Output

FIG. 15



430
AC POWER FROM XFMR SECOND -ARY
Z1
Z2
Z3
Rectifier
414
+
-
Shunt Regu- lator
432
D1
V1
C1
416
Q13
Q14
Q11
Q12
To Coil
418
Regul- ator for Local Fiber Optic and Control Circuits

FIG 16

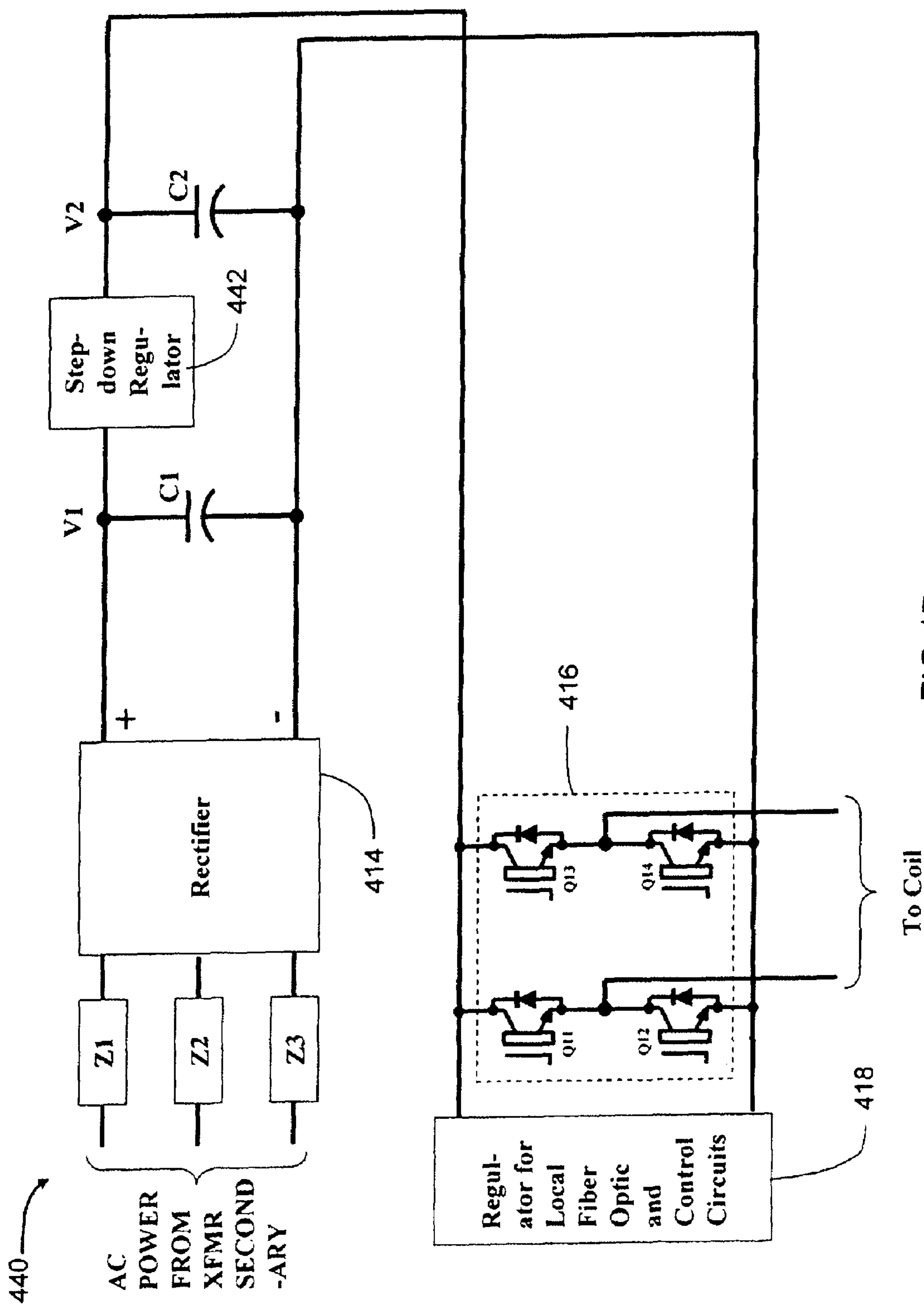

440
AC POWER FROM XFMR SECOND -ARY
Z1
Z2
Z3
Rectifier
414
+
-
V1
C1
Step-down Regu-lator
442
V2
C2
Q11
Q12
Q13
Q14
416
To Coil
Regul-ator for Local Fiber Optic and Control Circuits
418

FIG 17

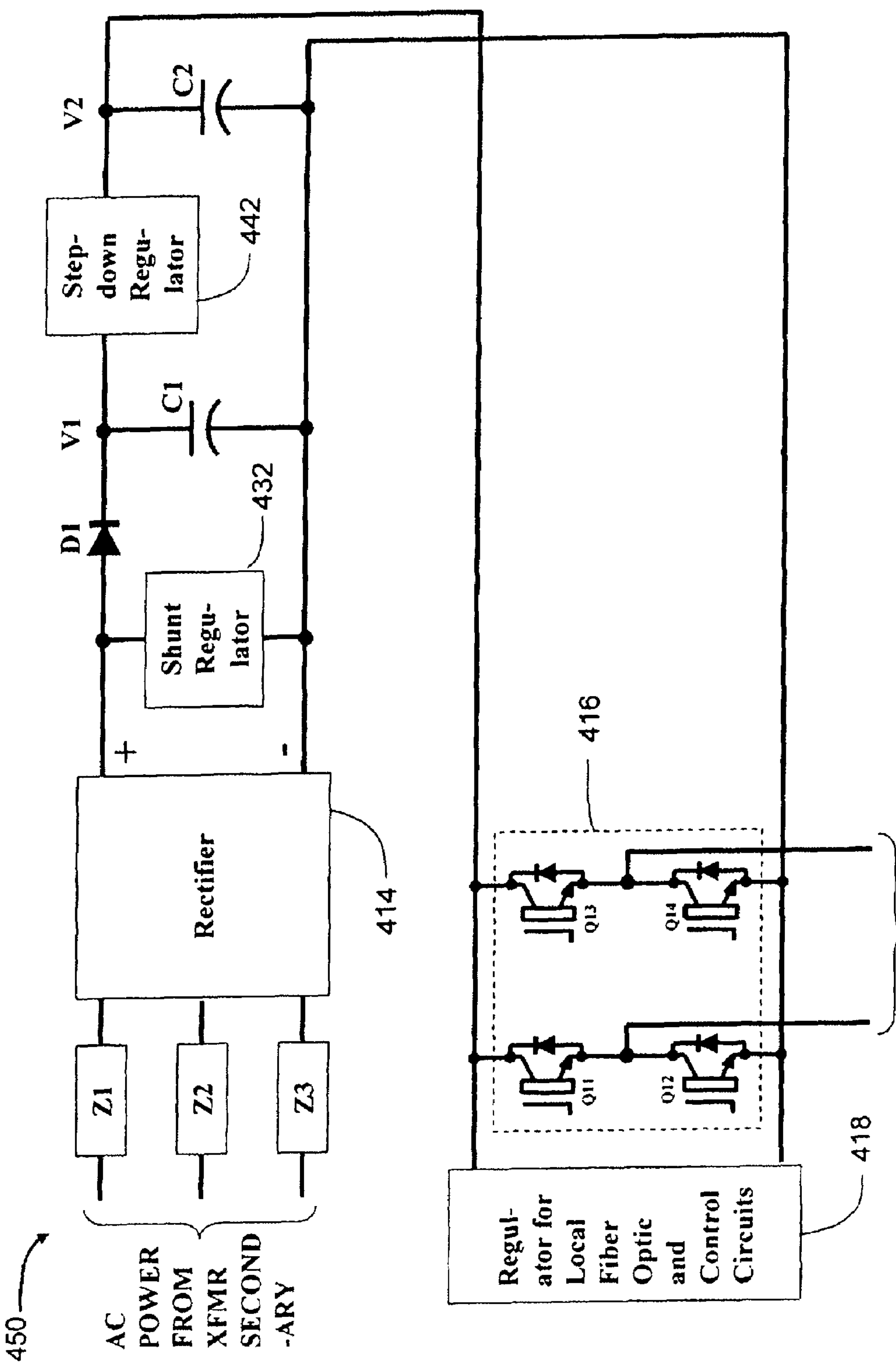

450
AC
POWER
FROM
XFMR
SECOND
-ARY
Z1
Z2
Z3
Rectifier
414
+
-
Shunt
Regu-
lator
432
D1
V1
C1
Step-
down
Regu-
lator
442
V2
C2
416
Q11
Q12
Q13
Q14
To Coil
Regul-
ator for
Local
Fiber
Optic
and
Control
Circuits
418

FIG 18

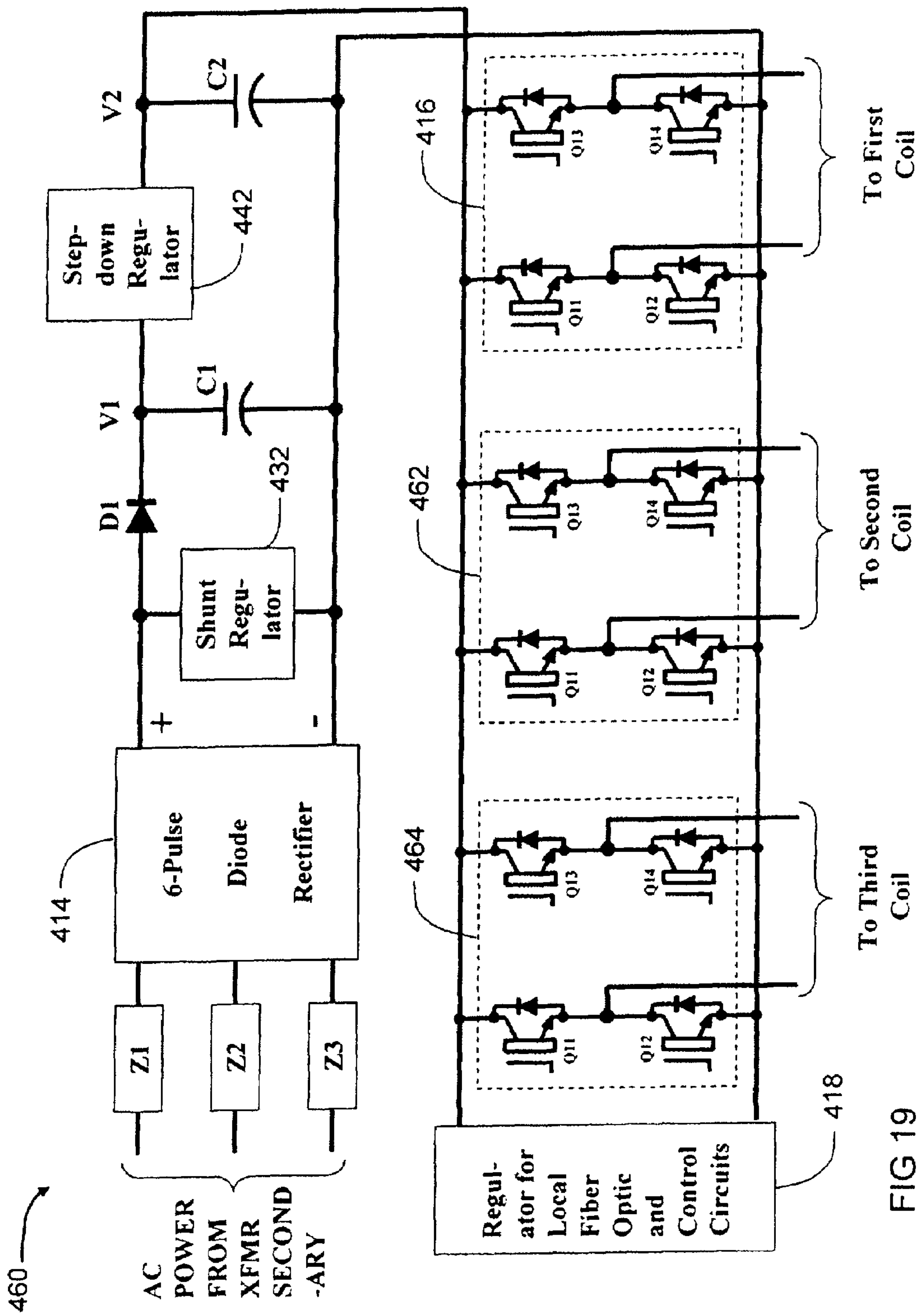

460
AC POWER FROM XFMR SECOND -ARY
Z1
Z2
Z3
414
6-Pulse Diode Rectifier
+
-
Shunt Regu- lator
432
D1
V1
C1
Step- down Regu- lator
442
V2
C2
416
462
464
Q11
Q12
Q13
Q14
To First Coil
To Second Coil
To Third Coil
Regul- ator for Local Fiber Optic and Control Circuits
418

FIG 19

SYSTEM FOR BYPASSING A POWER CELL OF A POWER SUPPLY

CROSS REFERENCE TO RELATED APPLICATION

This application claims the priority benefit of U.S. Provisional Patent Application No. 60/848,153, filed on Sep. 28, 2006.

NOT APPLICABLE

BACKGROUND

This application discloses an invention that is related, generally and in various embodiments, to a system for bypassing a power cell in a multi-cell power supply.

In certain applications, multi-cell power supplies utilize modular power cells to process power between a source and a load. Such modular power cells can be applied to a given power supply with various degrees of redundancy to improve the availability of the power supply. For example, FIG. **1** illustrates various embodiments of a power supply (e.g., an AC motor drive) having nine such power cells. The power cells in FIG. **1** are represented by a block having input terminals A, B, and C; and output terminals T**1** and T**2**. In FIG. **1**, a transformer or other multi-winding device **110** receives three-phase, medium-voltage power at its primary winding **112**, and delivers power to a load **130** such as a three-phase AC motor via an array of single-phase inverters (also referred to as power cells). Each phase of the power supply output is fed by a group of series-connected power cells, called herein a "phase-group".

The transformer **110** includes primary windings **112** that excite a number of secondary windings **114-122**. Although primary winding **112** is illustrated as having a star configuration, a mesh configuration is also possible. Further, although secondary windings **114-122** are illustrated as having a delta or an extended-delta configuration, other configurations of windings may be used as described in U.S. Pat. No. 5,625,545 to Hammond, the disclosure of which is incorporated herein by reference in its entirety. In the example of FIG. **1** there is a separate secondary winding for each power cell. However, the number of power cells and/or secondary windings illustrated in FIG. **1** is merely exemplary, and other numbers are possible. Additional details about such a power supply are disclosed in U.S. Pat. No. 5,625,545.

Any number of ranks of power cells are connected between the transformer **110** and the load **130**. A "rank" in the context of FIG. **1** is considered to be a three-phase set, or a group of three power cells established across each of the three phases of the power delivery system. Referring to FIG. **1**, rank **150** includes power cells **151-153**, rank **160** includes power cells **161-163**, and rank **170** includes power cells **171-173**. A master control system **195** sends command signals to local controls in each cell over fiber optics or another wired or wireless communications medium **190**. It should be noted that the number of cells per phase depicted in FIG. **1** is exemplary, and more than or less than three ranks may be possible in various embodiments.

FIG. **2** illustrates various embodiments of a power cell **210** which is representative of various embodiments of the power cells of FIG. **1**. The power cell **210** includes a three-phase diode-bridge rectifier **212**, one or more direct current (DC) capacitors **214**, and an H-bridge inverter **216**. The rectifier **212** converts the alternating current (AC) voltage received at cell input **218** (i.e., at input terminals A, B and C) to a substantially constant DC voltage that is supported by each capacitor **214** that is connected across the output of the rectifier **212**. The output stage of the power cell **210** includes an H-bridge inverter **216** which includes two poles, a left pole and a right pole, each with two switching devices. The inverter **216** transforms the DC voltage across the DC capacitors **214** to an AC output at the cell output **220** (i.e., across output terminals T**1** and T**2**) using pulse-width modulation (PWM) of the semiconductor devices in the H-bridge inverter **216**.

As shown in FIG. **2**, the power cell **210** may also include fuses **222** connected between the cell input **218** and the rectifier **212**. The fuses **222** may operate to help protect the power cell **210** in the event of a short-circuit failure. According to other embodiments, the power cell **210** is identical to or similar to those described in U.S. Pat. No. 5,986,909 and its derivative U.S. Pat. No. 6,222,284 to Hammond and Aiello, the disclosures of which are incorporated herein by reference in their entirety.

FIG. **3** illustrates various embodiments of a bypass device **230** connected to output terminals T**1** and T**2** of the power cell **210** of FIG. **2**. In general, when a given power cell of a multi-cell power supply fails in an open-circuit mode, the current through all the power cells in that phase-group will go to zero, and further operation is not possible. A power cell failure may be detected by comparing a cell output voltage to the commanded output, by checking or verifying cell components, through the use of diagnostics routines, etc. In the event that a given power cell should fail, it is possible to bypass the failed power cell and continue to operate the multi-cell power supply at reduced capacity.

The bypass device **230** is a single pole single throw (SPST) contactor, and includes a contact **232** and a coil **234**. As used herein, the term "contact" generally refers to a set of contacts having stationary portions and a movable portion. Accordingly, the contact **232** includes stationary portions and a movable portion which is controlled by the coil **234**. The bypass device **230** may be installed as an integral part of a converter subassembly in a drive unit. In other applications the bypass device **230** may be separately mounted. When the movable portion of the contact **232** is in a bypass position, a shunt path is created between the respective output lines connected to output terminals T**1** and T**2** of the power cell **210**. Stated differently, when the movable portion of the contact **232** is in a bypass position, the output of the failed power cell is shorted. Thus, when power cell **210** experiences a failure, current from other power cells in the phase group can be carried through the bypass device **230** connected to the failed power cell **210** instead of through the failed power cell **210** itself.

FIG. **4** illustrates various embodiments of a different bypass device **240** connected output terminals T**1** and T**2** of the power cell **210**. The bypass device **240** is a single pole double throw (SPDT) contactor, and includes a contact **242** and a coil **244**. The contact **242** includes stationary portions and a movable portion which is controlled by the coil **244**. When the movable portion of the contact **242** is in a bypass position, one of the output lines of the power cell **210** is disconnected (e.g., the output line connected to output terminal T**2** in FIG. **4**) and a shunt path is created between the output line connected to output terminal T**1** of the power cell **210** and a downstream portion of the output line connected to output terminal T**2** of the power cell **210**. The shunt path carries current from other power cells in the phase group which would otherwise pass through the power cell **210**. Thus, when power cell **210** experiences a failure, the output of the failed power cell is not shorted as is the case with the bypass configuration of FIG. **3**.

The bypass devices shown in FIGS. **3** and **4** do not operate to disconnect power to any of the input terminals A, B or C in the event of a power cell failure. Thus, in certain situations, if the failure of a given power cell is not severe enough to cause the fuses **222** (see FIG. **2**) to disconnect power to any two of input terminals A, B or C, the failure can continue to cause damage to the given power cell.

SUMMARY

In one general respect, this application discloses a system for bypassing a power cell in a multi-cell power supply. According to various embodiments, the system includes a multi-winding device having a primary winding and a plurality of three-phase secondary windings, and a plurality of power cells. Each power cell is connected to a different three-phase secondary winding of the multi-winding device. The system also includes a first contact connected to a first input terminal of at least one of the power cells, a second contact connected to a second input terminal of the at least one of the power cells, and a third contact connected to first and second output terminals of the at least one of the power cells.

According to other embodiments, the system includes a multi-winding device having a primary winding and a plurality of three-phase secondary windings, and a plurality of power cells. Each power cell is connected to a different three-phase secondary winding of the multi-winding device. The system also includes a first contactor connected to a first input terminal of at least one of the power cells, a second contactor connected to a second input terminal of the at least one of the power cells, and a third contactor connected to first and second output terminals of the at least one of the power cells.

DESCRIPTION OF THE DRAWINGS

Various embodiments of the invention are described herein by way of example in conjunction with the following figures.

FIG. **1** illustrates various embodiments of a power supply;

FIG. **2** illustrates various embodiments of a power cell of the power supply of FIG. **1**;

FIG. **3** illustrates various embodiments of a bypass device connected to an output of the power cell of FIG. **2**;

FIG. **4** illustrates various embodiments of a bypass device connected to an output of the power cell of FIG. **2**;

FIG. **5** illustrates various embodiments of a system for bypassing a power cell of a power supply;

FIG. **6** illustrates various embodiments of a system for bypassing a power cell of a power supply;

FIGS. **7-9** illustrate various embodiments of a bypass device;

FIG. **10** illustrates various embodiments of a system for bypassing a power cell of a power supply;

FIG. **11** illustrates various embodiments of a system for bypassing a power cell of a power supply;

FIG. **12** illustrates various embodiments of a system for bypassing a power cell of a power supply;

FIG. **13** illustrates various embodiments of a circuit for controlling a bypass device;

FIGS. **14** and **15** show the per-unit DC current and power available for various per-unit DC voltages at V**1** of the circuit of FIG. **13**;

FIG. **16** illustrates various embodiments of a circuit for controlling a bypass device;

FIG. **17** illustrates various embodiments of a circuit for controlling a bypass device;

FIG. **18** illustrates various embodiments of a circuit for controlling a bypass device; and

FIG. **19** illustrates various embodiments of a circuit for controlling a plurality of bypass devices.

DETAILED DESCRIPTION

It is to be understood that at least some of the figures and descriptions of the invention have been simplified to focus on elements that are relevant for a clear understanding of the invention, while eliminating, for purposes of clarity, other elements that those of ordinary skill in the art will appreciate may also comprise a portion of the invention. However, because such elements are well known in the art, and because they do not necessarily facilitate a better understanding of the invention, a description of such elements is not provided herein.

FIG. **5** illustrates various embodiments of a system **250** for bypassing a power cell (e.g., power cell **210**) of a power supply. As shown in FIG. **5**, the system **250** includes bypass device **252** connected to the output terminals T**1** and T**2**, a bypass device **254** connected to input terminal A, and a bypass device **256** connected to input terminal C. Although the system **250** is shown in FIG. **5** as having respective bypass devices connected to input terminals A and C, it will be appreciated that, according to other embodiments, the respective bypass devices may be connected to any two of the input terminals A, B and C.

The bypass devices **252**, **254**, **256** may be mechanically-driven, fluid-driven, electrically-driven, or solid state, as is described in the '909 and '284 patents. For purposes of simplicity, each bypass device will be described hereinafter in the context of a bypass device which includes one or more electrically-driven contactors which are connected to the output of a power cell. As described hereinafter, a given bypass device may be embodied as a single-pole single-throw (SPST) contactor, a single-pole double-throw (SPDT) contactor, or a multi-pole contactor.

Bypass device **252** is a single pole double throw (SPDT) contactor, and includes a contact **258** and a coil **260**. The contact **258** includes stationary portions and a movable portion which is controlled by the coil **260**. The bypass device **252** operates in a manner similar to that described hereinabove with respect to bypass device **240** of FIG. **4**. The bypass device **254** is a single pole single throw (SPST) contactor, and includes a contact **262** and a coil **264**. The contact **262** includes stationary portions and a movable portion which is controlled by the coil **264**. The bypass device **256** is a single pole single throw (SPST) contactor, and includes a contact **266** and a coil **268**. The contact **266** includes stationary portions and a movable portion which is controlled by the coil **268**. In general, in the event of a failure, bypass devices **254**, **256** disconnect the cell input power at substantially the same time that bypass device **252** creates a shunt path for the current that formerly passed through the failed power cell.

The condition associated with the creation of the described shunt path and the disconnection of cell input power from at least two of the cell input terminals may be referred to as "full-bypass". When the full bypass condition is present, no further power can flow into the failed cell. As described with respect to FIG. **2**, the fuses **222** of the power cell may operate to help protect the power cell in the event of a short-circuit failure. However, in certain situations (e.g., when fault current is low), the fuses **222** may not clear quickly enough to prevent further damage to the failed power cell. According to various embodiments, the bypass devices **254**, **256** are configured to act quicker than the fuses **222**, and the quicker action generally results in less damage to the failed power cell.

FIG. **6** illustrates various embodiments of a system **270** for bypassing a power cell (e.g., power cell **210**) of a power supply. The system **270** includes a single bypass device **272** which achieves the combined functionality of the bypass devices **252**, **254**, **256** of FIG. **5**. The bypass device **272** is a multi-pole contactor which includes a first contact **274** connected to the output terminals T**1** and T**2** of the power cell, a second contact **276** connected to the input terminal A, and a third contact **278** connected to the input terminal C. Each of the contacts **274**, **276**, **278** include stationary portions and a movable portion. Although the second and third contacts **276**, **278** are shown in FIG. **6** as being connected to input terminals A and C, it will be appreciated that, according to other embodiments, the second and third contacts **276**, **278** may be connected to any two of the input terminals A, B and C. The bypass device **272** also includes a single coil **280** which controls the movable portions of the contacts **274**, **276**, **278**.

FIGS. **7-9** illustrate various embodiments of a bypass device **300**. The bypass device is a multi-pole contactor, and may be identical to or similar to the bypass device **272** of FIG. **6**. The bypass device **300** includes a first contact which includes stationary portions **302**, **304** and movable portion **306**, a second contact which includes stationary portions **308**, **310** and a movable portion **312**, and a third contact which includes stationary portions **314**, **316**, **318**, **320** and a movable portion **322**. The bypass device **300** also includes a coil **324** which controls the movable portions **306**, **312**, **322** of the first, second and third contacts. The stationary portions **304**, **310** of the first and second contacts may be connected to any two of the input terminals A, B and C of a power cell. The stationary portions **314**, **318** of the third contact may be respectively connected to the output terminals T**1** and T**2** of a power cell. The movable portions **306**, **312**, **322** of the first, second and third contacts are shown in the normal or non-bypass position in FIGS. **7** and **8**, and are shown in the bypass position in FIG. **9**.

As shown in FIG. **7**, the bypass device **300** also includes electrical terminals **326** connected to the coil **324**, a steel frame **328** which surrounds the coil **324**, a first insulating plate **330** between the steel frame **328** and the stationary portions **304**, **308**, **310**, **312** of the first and second contacts, a second insulating plate **332** between the steel frame **328** and the stationary portions **314**, **316** of the third contact, and first and second support brackets **334**, **336**. The bypass device **300** further includes a non-magnetic shaft **338** which passes through the coil **324**, through openings in the steel frame **328**, through respective openings in first and second insulating plates **330**, **332**, and through respective openings of the first and second support brackets **334**, **336**.

Additionally, the bypass device **300** also includes a first biasing member **340** between the first support bracket **334** and a first end of the non-magnetic shaft **338**, a second biasing member **342** between the second support bracket **336** and a second end of the non-magnetic shaft, and a position sensing device **344** which is configured to provide an indication of the position (bypass or non-bypass) of the movable portions **306**, **312**, **322** of the first, second and third contacts.

Although not shown for purposes of simplicity in FIGS. **7-9**, one skilled in the art will appreciate that the bypass device **300** may further include a plunger (e.g., a cylindrical steel plunger) which can travel axially through an opening which extends from the first end of the coil **324** to the second end of the coil **324**, permanent magnets capable of holding the movable portions of the contacts in either the bypass or the non-bypass position without current being applied to the coil **324**, a first insulating bracket which carries the moving portions **306**, **312** of the first and second contacts, a second insulating bracket which carries the moving portion **322** of the third contact, etc.

In operation, permanent magnets (not shown) hold the plunger in either a first or a second position, which in turn holds the movable portions **306**, **312**, **322** of the contacts in either the non-bypass position or the bypass position. When the electrical terminals **326** receive pulses of current, the pulses of current are applied to the coil **324**, thereby generating a magnetic field. Depending on the polarity of the applied pulse and the position of the plunger, the applied pulse may or may not cause the plunger to change its position. For example, according to various embodiments, if the plunger is in the first position and the movable portions **306**, **312**, **322** of the contacts are in the non-bypass position, a positive current pulse will change the plunger from the first position to the second position, which in turn changes the movable portions **306**, **312**, **322** of the contacts from the non-bypass position to the bypass position. In contrast, if a negative current pulse is applied, the plunger will stay in the first position and the movable portions **306**, **312**, **322** of the contacts will stay in the non-bypass position.

Similarly, according to various embodiments, if the plunger is in the second position and the movable portions **306**, **312**, **322** of the contacts are in the bypass position, a negative current pulse will change the plunger from the second position to the first position, which in turn changes the movable portions **306**, **312**, **322** of the contacts from the bypass position to the non-bypass position. In contrast, if a positive current pulse is applied, the plunger will stay in the second position and the movable portions **306**, **312**, **322** of the contacts will stay in the bypass position.

FIG. **10** illustrates various embodiments of a system **350** for bypassing a power cell (e.g., power cell **210**) of a power supply. The system **350** is similar to the system **250** of FIG. **5**. The system **350** includes a first contact **352** connected to the output terminals T**1** and T**2** of the power cell, a second contact **354** connected to the input terminal A of the power cell, and a third contact **356** connected to the input terminal C of the power supply. Each of the contacts **352**, **354**, **356** include stationary portions and a movable portion. Although the second and third contacts **354**, **356** are shown in FIG. **10** as being connected to input terminals A and C, it will be appreciated that, according to other embodiments, the second and third contacts **354**, **356** may be connected to any two of the input terminals A, B and C.

The system **350** also includes a first coil **358** which controls the movable portions of the first contact **352**, a second coil **360** which controls the movable portion of the second contact **354**, and a third coil **362** which controls the movable portion of the third contact **356**. According to various embodiments, the coils **358**, **360**, **362** are embodied as contactor coils. According to other embodiments, the coils **358**, **360**, **362** are embodied as magnetic latching coils which do not need to have continuous power applied to the coils in order to hold the plunger in its first or second position and/or to hold the moving portions of the contacts **352**, **354**, **356** in the non-bypass or bypass position. The first contact **352** and the first coil **358** may collectively comprise a first contactor, the second contact **354** and the second coil **360** may collectively comprise a second contactor, and the third contact **356** and the third coil **362** may collectively comprise a third contactor.

The system **350** further includes a first local printed circuit board **364** in communication with the first coil **358**, a second local printed circuit board **366** in communication with the second coil **360**, and a third local printed circuit board **368** in communication with the third coil **362**. Each of local printed circuit boards **364**, **366**, **368** are configured to control the respective movable portions of the contacts **352**, **354**, **356** via the respective coils **358**, **360**, **362**. In general, each of the local printed circuit boards **364**, **366**, **368** are configured to receive commands from, and report status to, a master control device (e.g., master control system **195** of FIG. **1**) that is held near ground potential. Each of the local printed circuit boards **364**, **366**, **368** are also configured to deliver pulses of energy to the respective coils **358**, **360**, **362** as needed to change the position of the movable portions of the respective contacts **352**, **354**, **356**, and to recognize the position of the movable portions of the respective contacts **352**, **354**, **356**. Each of the local printed circuit boards **364**, **366**, **368** may obtain control power from the input lines which are connected to input terminals A, B, C of the power cell. As shown in FIG. **10**, one or more position sensing devices (labeled PSD in FIG. **10**) may be utilized to provide the local printed circuit boards **364**, **366**, **368** with the respective positions of the movable portions of the contacts **352**, **354**, **356**. According to various embodiments, the position sensing devices may be embodied as switching devices, hall effect sensors, optical sensors, etc.

For embodiments where the coils **358**, **360**, **362** are latching coils, the local printed circuit boards **364**, **366**, **368** may each include a DC capacitor which can store enough energy to switch the plunger and/or the movable portions of the respective contacts **352**, **354**, **356** between positions. Each of the local printed circuit boards **364**, **366**, **368** may also include a power supply which restores the stored energy after a switching event, using AC power from the input lines connected to the input terminals A, B, C of the power cell.

FIG. **11** illustrates various embodiments of a system **370** for bypassing a power cell (e.g., power cell **210**) of a power supply. The system **370** is similar to the system **350** of FIG. **10**. The system **370** includes a first contact **372** connected to the output terminals T**1** and T**2** of the power cell, a second contact **374** connected to the input terminal A of the power cell, and a third contact **376** connected to the input terminal C of the power supply. Each of the contacts **372**, **374**, **376** include stationary portions and a movable portion. Although the second and third contacts **374**, **376** are shown in FIG. **11** as being connected to input terminals A and C, it will be appreciated that, according to other embodiments, the second and third contacts **374**, **376** may be connected to any two of the input terminals A, B and C.

The system **370** also includes a first coil **378** which controls the movable portions of the first contact **372**, a second coil **380** which controls the movable portion of the second contact **374**, and a third coil **382** which controls the movable portion of the third contact **376**. According to various embodiments, the coils **378**, **380**, **372** are embodied as contactor coils. According to other embodiments, the coils **378**, **380**, **382** are embodied as magnetic latching coils which do not need to have continuous power applied to the coils in order to hold the plunger in its first or second position and/or to hold the moving portions of the contacts **372**, **374**, **376** in the non-bypass or bypass position.

According to various embodiments, the first contact **372** and the first coil **378** are portions of a first bypass device, the second contact **374** and the second coil **380** are portions of a second bypass device, and the third contact **376** and the third coil **382** are portions of a third bypass device. For such embodiments, the system **370** includes a plurality of bypass devices.

In contrast to the system **350** of FIG. **10**, the system **370** includes a single local printed circuit board **384** which is in communication with the first coil **378**, the second coil **380**, and the third coil **382**. The local printed circuit board **384** is configured to control the respective movable portions of the contacts **372**, **374**, **376** via the respective coils **378**, **380**, **382**. Thus, the local printed circuit board **384** is similar to the local printed circuit boards described with respect to FIG. **10**, but is different in that the local printed circuit board **384** is configured to drive three coils and recognize the respective positions of the movable portions of three contacts. In general, the local printed circuit board **384** is configured to receive commands from, and report status to, a master control device (e.g., master control system **195** of FIG. **1**) that is held near ground potential.

The local printed circuit board **384** is also configured to deliver pulses of energy to the coils **378**, **380**, **382** as needed to change the position of the movable portions of the respective contacts **372**, **374**, **376**, and to detect the position of the movable portions of the respective contacts **372**, **374**, **376**. The local printed circuit board **384** may obtain control power from the input lines which are connected to input terminals A, B, C of the power cell. As shown in FIG. **11**, one or more position sensing devices (labeled PSD in FIG. **11**) may be utilized to provide the local printed circuit board **384** with the respective positions of the movable portions of the contacts **372**, **374**, **376**. According to various embodiments, the position sensing devices may be embodied as switching devices, hall effect sensors, optical sensors, etc.

For embodiments where the coils **378**, **380**, **382** are latching coils, the local printed circuit board **384** may include a DC capacitor which can store enough energy to switch the plunger and/or the movable portions of the contacts **352**, **354**, **356** between positions. The local printed circuit board **384** may also include a power supply which restores the stored energy after a switching event, using AC power from the input lines connected to the input terminals A, B, C of the power cell.

FIG. **12** illustrates various embodiments of a system **390** for bypassing a power cell (e.g., power cell **210**) of a power supply. The system **390** is similar to the system **370** of FIG. **11**. The system **390** includes a bypass device **392** which may be embodied as a multi-pole contactor. The bypass device **392** may be identical to or similar to the bypass device **300** shown in FIGS. **7-9**. The bypass device **392** includes a first contact **394** connected to the output terminals T**1** and T**2** of the power cell, a second contact **396** connected to the input terminal A of the power cell, and a third contact **398** connected to the input terminal C of the power supply. Each of the contacts **394**, **396**, **398** include stationary portions and a movable portion. Although the second and third contacts **396**, **398** are shown in FIG. **12** as being connected to input terminals A and C, it will be appreciated that, according to other embodiments, the second and third contacts **396**, **398** may be connected to any two of the input terminals A, B and C.

In contrast to system **370** of FIG. **11**, the system **390** includes a single coil **400** which controls the movable portions of the first, second and third contacts **394**, **396**, **398**. According to various embodiments, the coil **400** is embodied as a contactor coil. According to other embodiments, the coil **400** is embodied as a magnetic latching coil which does not need to have continuous power applied to the coil in order to hold the plunger in its first or second position and/or to hold the moving portions of the contacts **394**, **396**, **398** in the non-bypass or bypass position.

The system **390** also includes a single local printed circuit board **402** which is in communication with the coil **400**. The local printed circuit board **402** is configured to control the respective movable portions of the contacts **394**, **396**, **398** via the coil **400**. In general, the local printed circuit board **402** is configured to receive commands from, and report status to, a master control device (e.g., master control system **195** of FIG. **1**) that is held near ground potential.

The local printed circuit board **402** is also configured to deliver pulses of energy to the coil **400** as needed to change the position of the movable portions of the respective contacts **394**, **396**, **398**, and to recognize the position of the movable portions of the respective contacts **394**, **396**, **398**. The local printed circuit board **402** may obtain control power from the input lines which are connected to input terminals A, B, C of the power cell. As shown in FIG. **12**, a position sensing device (labeled PSD in FIG. **12**) may be utilized to provide the local printed circuit board **402** with the respective positions of the movable portions of the contacts **394**, **396**, **398**. According to various embodiments, the position sensing device may be embodied as a switching device, a hall effect sensor, an optical sensor, etc.

For embodiments where the coil **400** is a latching coil, the local printed circuit board **402** may also include a DC capacitor which can store enough energy to switch the plunger and/or the movable portions of the contacts **394**, **396**, **398** between positions. The local printed circuit board **402** may also include a power supply which restores the stored energy after a switching event, using AC power from the input lines connected to the input terminals A, B, C of the power cell.

FIG. **13** illustrates various embodiments of a circuit **410** for controlling a bypass device (e.g., bypass device **392** of FIG. **12**). The circuit **410** may be embodied as a printed circuit board having integrated circuits, discrete components, and combinations thereof. The circuit **410** may be utilized, for example, to provide the functionality of one or more of the local printed circuit boards described hereinabove. For reasons of simplicity, the circuit **410** will be described as a printed circuit board in the context of its use in the system **390** of FIG. **12**.

The circuit board **410** includes an on-board DC control power supply **412**. The power supply **412** includes series limiting impedance components Z**1**, Z**2**, Z**3** and a rectifier **414**. The impedance components Z**1**, Z**2**, Z**3** are respectively connected to three input lines which are connected to input terminals A, B, C of a power cell (e.g., power cell **210**). The impedance components Z**1**, Z**2**, Z**3** may be embodied, for example, to include capacitors, and may be sized such that if one fails, the other two can continue to operate to limit the available current. According to various implementations, the impedance components Z**1**, Z**2**, Z**3** may also be embodied to include resistors in series with the capacitors. According to various embodiments, the rectifier **414** is a six-pulse diode rectifier. The printed circuit board **410** also includes a capacitor C**1** connected to the power supply **412**, a group of switching devices **416** connected to the capacitor C**1**, and another regulator **418** connected to the capacitor C**1**. As shown in FIG. **13**, the group of switching devices **416** is also connected to a coil (e.g., coil **400** of the bypass device **392** of FIG. **12**).

The capacitor C1 is sized to be able to store the amount of energy needed to cause the plunger and/or the movable portions of the contacts to change positions when such energy is applied to the coil. Capacitor C**1** may be embodied as, for example, an electrolytic capacitor, an ultra capacitor, a film type capacitor, etc. Although the capacitor C**1** is shown as a single capacitor in FIG. **13**, it will be appreciated that capacitor C**1** may be embodied as multiple capacitors (e.g., three capacitors) connected in series or parallel.

The group of switching devices **416** is configured to apply either a positive or a negative current pulse to the coil. The individual switching devices may be embodied as, for example, mosfets, insulated gate bipolar transistors, etc. Although each coil described herein is described in the context of a single winding for purposes of simplicity, one skilled in the art will appreciate that according to other embodiments, a given coil can comprise two redundant windings, with one winding being connected to receive the positive current pulse and the other winding connected to receive the negative current pulse. Thus, although the group of switching devices **416** is shown in FIG. **13** as having four individual switching devices, according to other embodiments, the group of switching devices **416** may include a different number of switching devices (e.g., two switching devices). The regulator **418** may be configured to condition the voltage of the power supply **412** to operate fiber optic and control circuits.

In operation, the power supply **412** receives AC power from the input lines connected to the input terminals A, B, C of the power cell. The AC power flows through the series limiting impedance components Z**1**, Z**2**, Z**3** to the rectifier **414**. The rectifier **414** converts the AC power to DC power, and the DC power charges capacitor C**1** to the voltage at V**1**. The voltage at V**1** is applied to the group of switching, devices **416**, and depending on the respective states (e.g., on, off) of the individual switching devices, the group of switching devices **416** may deliver a positive or a negative current pulse to the coil. The positive or negative current pulses create a magnetic field which is utilized to change the position of the plunger and/or the movable portions of the contacts which are connected to the input and output terminals of the power cell.

When the capacitor C**1** is discharging, the group of switching devices **416** may employ pulse-width modulation (PWM) to maintain a substantially constant average voltage (or constant current) on the coil. In general, when the capacitor C**1** is discharging, the voltage across the capacitor C**1** is equal to or greater than approximately one-half of its worst case initial voltage. When the coil is a latching coil and none of the switching devices are in the "on" state, the plunger and/or the movable portions of the contacts may maintain their existing positions by magnetic latching. During the time that the plunger and/or the movable portions of the contacts maintain their existing positions by magnetic latching, the power supply **412** can recharge the capacitor C**1**.

In general, the capacitor C**1**, the group of switching devices **416**, the coil connected to the group of switching devices **416**, and the regulator **418** should each be rated for the maximum voltage expected to be delivered to the power cell (i.e., the peak of the input AC line-to-line voltage delivered to the power cell). Additionally, as the voltage at V**1** can vary from the maximum voltage delivered to the power cell down to approximately one-half of the lowest voltage delivered to the power cell (i.e., when capacitor C**1** is discharging), the coil should also be designed to control the position of the plunger and/or the movable portions of the contacts even when approximately one-half of the lowest voltage delivered to the power cell is applied to the coil.

With no DC load, the rectifier **414** may generate a DC output voltage at V**1** which is substantially equal to the peak of the input line-to-line AC voltage feeding the power cell. In some embodiments, a power supply may function with power cells having a range of nominal voltage ratings from about 630 VAC to about 750 VAC. The power supply may also need to tolerate a range of utility voltage from 110% to 70% of nominal. Thus, the peak of the input AC line-to-line voltage (and hence the no-load DC voltage at V**1**) may be as high as 1167 volts, and as low as 686 volts. According to other embodiments, other values are possible.

With a short (i.e., line-to-neutral) on the DC output, the DC output current is effectively limited to approximately 0.55

times the peak of the input AC line-to-line voltage, divided by the impedance of the impedance components Z1, Z2, Z3. For example, if the impedance components Z1, Z2, Z3 are embodied as 0.1 μfd capacitors and the peak AC voltage is 1167 volts at 60 Hertz, the maximum available DC current would be approximately 0.024 amperes. FIGS. **14** and **15** show the per-unit DC current and power available, for various per-unit DC voltages at V**1**. The per-unit values are based on open-circuit and short-circuit values defined above.

FIG. **16** illustrates various embodiments of a circuit **430** for controlling a bypass device (e.g., bypass device **392** of FIG. **12**). The circuit **430** is similar to the circuit **410** of FIG. **13**, and further includes a shunt regulator **432** connected to the rectifier **414** and a diode D**1** connected to the shunt regulator **432**. The shunt regulator **432** operates to limit the voltage on capacitor C**1** to a particular voltage (e.g., 400 volts). For example, whenever the voltage at V**1** exceeds a particular voltage (e.g., 400 volts), the shunt regulator **432** may short out the rectifier **414**. The diode D**1** prevents capacitor C**1** from discharging into the shunt regulator **432**.

In general, for such embodiments, the capacitor C**1**, the group of switching devices **416**, the coil connected to the group of switching devices **416** (e.g., coil **400** of the bypass device **392** of FIG. **12**), and the regulator **418** could each be rated for the particular voltage (e.g., 400 volts) which is less than the maximum voltage expected to be delivered to the power cell (i.e., the peak of the input AC line-to-line voltage delivered to the power cell). If the minimum no-load voltage available from the diode D**1** is, for example, 686 volts, the voltage at V**1** would always reach 400 volts for a nominal cell voltage rating as low as 630 VAC, even with utility variations from 110% to 70% of nominal. If the maximum short-circuit current available from the rectifier **414** is limited to, for example, 0.024 amperes (see FIGS. **14** and **15**), no harm occurs when the rectifier **414** is shorted out by the shunt regulator **432**. For such embodiments, as the voltage at V**1** can vary from the maximum voltage (e.g., 400 volts) down to approximately one-half of the maximum voltage (e.g., 200 volts), the coil should also be designed to control the position of the plunger and/or the movable portions of the contacts even when the lowest voltage at V**1** is applied to the coil.

FIG. **17** illustrates various embodiments of a circuit **440** for controlling a bypass device (e.g., bypass device **392** of FIG. **12**). The circuit **440** is similar to the circuit **410** of FIG. **13**, and further includes a step-down regulator **442** connected to the capacitor C**1**, and a capacitor C**2** connected to the step-down regulator **442**. The step-down regulator **442** operates to step-down the variable voltage at V**1** to a lower fixed voltage at V**2**. As the voltage applied to the group of switches **416**, the coil connected to the group of switches **416** (e.g., coil **400** of the bypass device **392** of FIG. **12**), and the regulator **418** is the lower voltage at V**2**, the group of switching devices **416**, the coil, and the regulator **418** may each be rated for the lower voltage. According to various embodiments, the voltage at V**2** may be low enough to allow for the use of integrated circuits for the group of switches **416** and the regulator **418**. Even if the voltage at V**1** sags significantly while the capacitor C**1** discharges its stored energy, the voltage at V**2** could be held nearly constant, provided that the voltage provided by the step-down regulator **442** is less than the minimum voltage that appeared at V**1** during the sag. For such embodiments, pulse width modulation control of the switching devices of the H-bridge **416** is not necessary.

FIG. **18** illustrates various embodiments of a circuit **450** for controlling a bypass device (e.g., bypass device **392** of FIG. **12**). The circuit **450** is similar to the circuit **410** of FIG. **13**, and further includes a shunt regulator **432** connected to the rectifier **414**, a diode D**1** connected to the shunt regulator **432**, a step-down regulator **442** connected to the capacitor C**1**, and a capacitor C**2** connected to the step-down regulator **442**. The added components operate as described in FIGS. **16** and **17**, and such operation can result in the voltage at V**1** being, for example, between 200 volts DC and 400 volts DC. For such embodiments, the lower DC voltages at V**1** would reduce the peak voltage stress on the shunt regulator **432**, the capacitor C**1**, and the step-down regulator **442**. For example, the peak voltage stress on the shunt regulator **432**, the capacitor C**1**, and the step-down regulator **442** may be reduced from 1167 volts DC to 400 volts DC. The voltage at V**2** could be held nearly constant, at a low value. For such embodiments, pulse width modulation control of the group of switching devices **416** is not necessary, and integrated circuits can be utilized for the group of switches **416** and the regulator **418**. Also, the amount of insulation needed for the coil connected to the group of switching devices **416** (e.g., coil **400** of the bypass device **392** of FIG. **12**) could be reduced.

FIG. **19** illustrates various embodiments of a circuit **460** for controlling a plurality of bypass devices (e.g., the bypass devices of FIG. **11**). The circuit **460** is similar to the circuit **450** of FIG. **18**, but includes three groups of switching devices **416**, **462**, **464** which are each connected to the capacitor C**2**. The additional groups of switching devices **462**, **464** are similar to the group of switching devices **416** as described hereinabove. Each of the groups of switching devices **416**, **462**, **464** are also connected to a different coil (e.g., coils **378**, **380**, **382** of FIG. **11**) which forms a portion of a different bypass device. Thus, one skilled in the art will appreciate that the circuit **460** may be utilized, for example, to provide the functionality of the local printed circuit board **384** of FIG. **11**, which controls the three coils **378**, **380**, **382** which control the respective positions of the plunger and/or the movable portions of contacts **372**, **374**, **376**. For such embodiments, the capacitor C**1** is sized to be able to store the amount of energy needed to cause the plunger and/or the movable portions of all the contacts to concurrently change positions when such energy is applied to all the coils.

While several embodiments of the invention have been described herein by way of example, those skilled in the art will appreciate that various modifications, alterations, and adaptions to the described embodiments may be realized without departing from the spirit and scope of the invention defined by the appended claims.

What is claimed is:

1. A system, comprising:

a multi-winding device having a primary winding and a plurality of three-phase secondary windings;

a plurality of power cells, wherein each power cell is connected to a different three-phase secondary winding of the multi-winding device;

a stationary portion of a first contactor connected to a first input terminal of at least one of the power cells;

a stationary portion of a second contactor connected to a second input terminal of the at least one of the power cells; and

a stationary portion of a third contactor connected to first and second output terminals of the at least one of the power cells.

2. The system of claim **1**, further comprising:

a first coil coupled to a movable portion of the first contactor;

a second coil coupled to a movable portion of the second contactor; and

a third coil coupled to a movable portion of the third contactor.

3. The system of claim 2, wherein at least one of the first, second and third coils is a latching coil.

4. The system of claim 2, further comprising a control circuit connected to at least one of the first, second and third coils.

5. The system of claim 4, wherein the control circuit is connected to the three-phase secondary winding to which the at least one of the power cells is connected.

6. The system of claim 4, wherein the control circuit comprises a printed circuit board.

7. The system of claim 4, wherein the control circuit comprises:

an impedance component connected to the three-phase secondary winding to which the at least one of the power cells is connected;

a rectifier connected to the impedance component;

a capacitor connected to the rectifier; and

a group of switching devices connected to the capacitor and at least one of the first, second and third coils.

8. The system of claim 7, wherein the rectifier is a six-pulse rectifier.

9. The system of claim 7, wherein the group of switching devices is an integrated circuit.

10. The system of claim 7, further comprising a second regulator connected to the capacitor.

11. The system of claim 10, wherein the second regulator is an integrated circuit.

12. The system of claim 7, further comprising:

a shunt regulator connected to the rectifier; and

a diode connected between the shunt regulator and the capacitor.

13. The system of claim 7, further comprising:

a step-down regulator connected to the capacitor; and

a second capacitor connected between the step-down regulator and the group of switching devices.

14. The system of claim 7, further comprising:

a shunt regulator connected to the rectifier;

a diode connected between the shunt regulator and the capacitor;

a step-down regulator connected to the capacitor; and

a second capacitor connected between the step-down regulator and the group of switching devices.

15. The system of claim 4, further comprising a switching device connected to the control circuit and at least one of the coils.

16. A system, comprising:

a multi-winding device having a primary winding and a plurality of three-phase secondary windings;

a plurality of power cells, wherein each power cell is connected to a different three-phase secondary winding of the multi-winding device;

a first contactor connected to a first input terminal of at least one of the power cells;

a second contactor connected to a second input terminal of the at least one of the power cells; and

a third contactor connected to first and second output terminals of the at least one of the power cells.

17. The system of claim 16, wherein:

the first contactor comprises a first coil;

the second contactor comprises a second coil; and

the third contactor comprises a third coil.

18. The system of claim 16, further comprising a control circuit connected to at least one of the first, second and third contactors.

19. The system of claim 18, wherein the control circuit comprises a printed circuit board.

20. The system of claim 18, wherein the control circuit comprises:

an impedance component connected to the three-phase secondary winding to which the at least one of the power cells is connected;

a rectifier connected to the impedance component;

a capacitor connected to the rectifier; and

a group of switching devices connected to the capacitor and at least one of the first, second and third coils.

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